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RAINFALL AND TREE GROWTH IN THE GREAT BASIN

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BY

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INTRODUCTION

In the autumn of 1931 the writer collected data bearing on rainfall fluctuations in the northwestern part of the Great Basin since the first settlement of the region by white men. The study was suggested by Dr. Isaiah Bowman, and the expenses of the field work were defrayed by the Carnegie Institution of Washington. Officials and long-time inhabitants were interviewed, newspaper files and libraries consulted, lake levels observed and samples of lake sediments collected, and radial samples were sawed from stumps of trees growing on mountain slopes near the desert. Later, relevant literature was consulted in the Library of Congress and the library of the American Geographical Society. The Great Salt Lake region is included in this survey, although no field work was done there.

Because of the supreme importance of water in the deserts and semideserts of the Great Basin, explorers, emigrants, settlers, and historians made notes on the precipitation, on the water supply of rivers and lakes, and on crops and grazing conditions long before systematic instrumental observations were begun. Since official records of rainfall and runoff have been kept, settlers have observed and newspapers have recorded facts and conditions that are often more telling than the statistical figures. These traditional and historical data are especially valuable because they emphasize and date the extreme conditions, such as unusual floods and runoffs, high lake levels, severe droughts and economic catastrophies, and thereby help in determining the existence and trend of fluctuations in precipitation. However, these data are also sporadic, local, subjective, and inaccurate or misleading. Least reliable are the narratives about early emigrant trains to the West. Statements by settlers are usually correct as to facts but not always as to time. Average conditions and gradual changes have been given little thought, and therefore the data are notoriously incomplete. In some regions occurrences and conditions have been recorded or remembered by observant inhabitants; elsewhere no comparable information may be available for entire decades.

It seemed possible that the lake sediments might record stages of high and low water or complete desiccation. The exceptional opportunity offered by the partial or complete desiccation of most of the lakes in the northwestern Great Basin in 1931 was therefore used to study and sample their deposits. However, the results of the study were either negative or indefinite. The surface crusts of salt or clay that form when most of the lakes dry up are not preserved when the lake bottoms are again covered by water, and unfortunately the nature of the plant and animal remains and of the partly organic sediments was not determined.[1]

Radial samples were sawed from many tree stumps along the boundary between the forest and the semidesert at Susanville in northeastern California and near Lakeview in south-central Oregon. The results of the study of this material, compiled in the Susanville and the Lakeview ring curves (Plate I, c, e),[2] are published as Part II of the present volume. They show that tree-ring curves alone permit only general and somewhat conditional conclusions concerning past rainfall fluctuations but acquire greater significance when combined with other evidence.

There are rainfall and runoff data for the Great Basin for the periods since 1870 and 1899, respectively. Precipitation and stream-flow records have been compiled separately for five regions: (1) Lake County in Oregon north of the Nevada-California boundary, (2) the Great Basin region of northeastern California, i.e. the northeastern corner of the state, or Modoc and Lassen counties, (3) the Truckee-Carson-Walker region, or western Nevada and adjacent California, (4) the Humboldt region of northern Nevada, and (5) the Great Salt Lake basin in Utah.

For each station the precipitation and the runoff have been calculated, not for calendar years, but for "rainfall years" and "water years," beginning October 1 and ending September 30. Consequently in the following discussion the terms "annual rainfall," "annual runoff," and "year" are ordinarily to be understood as applying to these rainfall and water years. For the sake of brevity the rainfall, for instance, of the rainfall year October 1920-September 1921 is called the "rainfall of 1921."

In order to modify an otherwise undue influence of individual stations with very great or very small rainfall the precipitation of each region has been calculated in the following manner. The annual rainfall for each rainfall year, October-September, has been computed from the Weather Bureau data for each station and then recalculated as a percentage of the mean annual precipitation at the station for the entire period covered by the instrumental record. These percentages at the different stations have been added for each rainfall year, and the sum has been divided by the number of stations. The means thus obtained represent the annual rainfall for the region as given in the accompanying curves. In other words, the curves show the mean precipitation for the region for each year after the total precipitation at each of the several stations during the entire period of record has been weighted equally with that of every other station. The annual stream flow,

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[1] Shrock and Hunzicker (1935). (For more detailed references see List of References, pp. 89-91 below.)

[2] The plates will be found in the pocket at the end of the book. In the List of Illustrations references are given to the pages of the text upon which explanations of certain of the graphs will be found.

October-September, of each region has been calculated after the same method from data in *U. S. Geological Survey Water-Supply Papers* or from papers published by the State Engineers or from both of these sources. In addition, a precipitation curve, beginning 1850, has been computed for Sacramento, San Francisco, and Red Bluff (Plate I, a).

The rainfall and runoff curves, as well as the tree-growth graphs, have been smoothed after the formula $\frac{1}{4}(a+2b+c)$, the quotient being substituted for the value b. The smoothing has been applied graphically. Of three successive points, a, b, c, in a graph, a and c have been connected by a line, completing a triangle. The point halfway between the center of the drawn line, or base, and the opposite corner of the triangle gives the position of the smoothed point substituted for b. The graphs have been smoothed twice in this manner.

Both the rainfall and the runoff curves undergo a broad general decline towards the present, but the downward trend of the stream-flow graphs is not only greater but clearly excessive. This is due, at least largely, to increasing diversions of water above the gauging stations. The runoff curves of Lake County, Modoc and Lassen counties (Plate II, k, n), and the Truckee-Carson-Walker region (Plate I, g) therefore have each been adjusted to the broad trend shown by the precipitation curves of the same region. To this end straight or slightly curved trend lines were drawn from the graphs. The trend line of a rainfall curve was then copied on ruled paper, the point of intersection with the horizontal average (100 per cent) line being that of the corresponding runoff curve. The deviations of the runoff curve from *its* trend line were then transferred to the new trend line, that of the rainfall. The runoff curves of the Humboldt region and the Great Salt Lake region (Plate II, q, t) were similarly changed to a trend lying halfway between those of the rainfall and the measured stream flow. In order to combine the miscellaneous data skeleton plots are given (Plate II, a-h).

To all those who have supplied data or aided the work in other ways—President Isaiah Bowman of the Johns Hopkins University, the Carnegie Institution of Washington, government officials, newspaper and business men, engineers, ranchers, and his wife, Ada Antevs—the writer conveys his sincere thanks.

PART I

RAINFALL FLUCTUATIONS DURING THE PAST HUNDRED YEARS

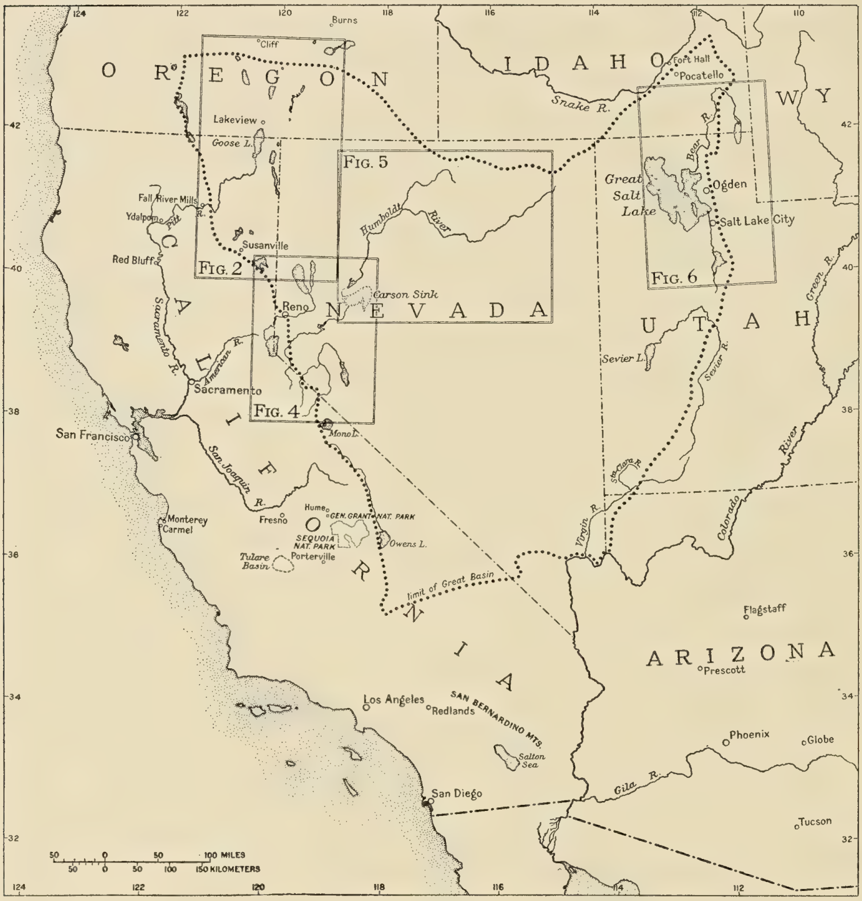

Fig. 1—Location map of the Great Basin and vicinity. Scale, 1: 12,000,000. The rectangles show the areas covered by the other location maps in the present work.

CHAPTER I

LAKE COUNTY, SOUTH-CENTRAL OREGON

THE PERIOD BEFORE 1891

Judging from a more-than-average width of the tree rings at Susanville, California, and Lakeview, Oregon, the first quarter of the nineteenth century was a time of ample water supply in the part of the Great Basin that comprises the northeastern corner of California and adjacent Oregon. From 1801 to 1828 there does not seem to have been a single drought year. The generally moist period was terminated by an abrupt and severe drought in 1829; a narrow ring for that year shows that growth was checked in the trees both at Susanville and at Lakeview. Indeed, for the 150 years previous to 1932, only one ring is narrower—that of 1924—though at Lakeview the ring of 1829 is equalled by those of a few seasons. After remaining low for some years the water supply increased to a fair maximum in 1836-38. Then it underwent a general decrease till about 1844, after which the evidence is somewhat conflicting. That there was a long and severe drought during the eighteen-forties is indicated by small ring widths and by the exceptionally low stand of Goose Lake about 1850. Yet the drought may not have been so extreme as the growth minimum at Lakeview suggests, for this is contradicted by data given in the following paragraphs and by the much less pronounced growth minimum at Susanville. The growth minimum in the Lakeview trees could be in part referable to damages by insects, fire, or the like.[1]

In December 1843 Summer Lake, Lake Abert, and the Warner Lakes in Oregon north of the Nevada-California boundary seem to have been near their normal levels, judging from Frémont's report.[2] Summer Lake, normally about 5 by 15 miles in area, is fed mostly by the Ana River, which rises from large springs a few miles north of the lake. Lake Abert, which in 1908 measured 5 by 15 miles,[3] was originally supplied by the Chewaucan River, Crooked Creek, and large springs in the lake; but for many years most or all of the water of the rivers has been diverted for irrigation. The Warner Lakes, which drain northward and are separated by swamps and short streams, form a chain southeast of Lake Abert. The normal elevation of Crump Lake, second in order of the Warner Lakes from the south, is 12 feet higher than that of

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[1] See below, pp. 68, 72, 79-81.

[2] Frémont (1845), 207, 209, 210; *Lake County Examiner,* Sept. 2, 1926.

Waring (1908), Pl. II.

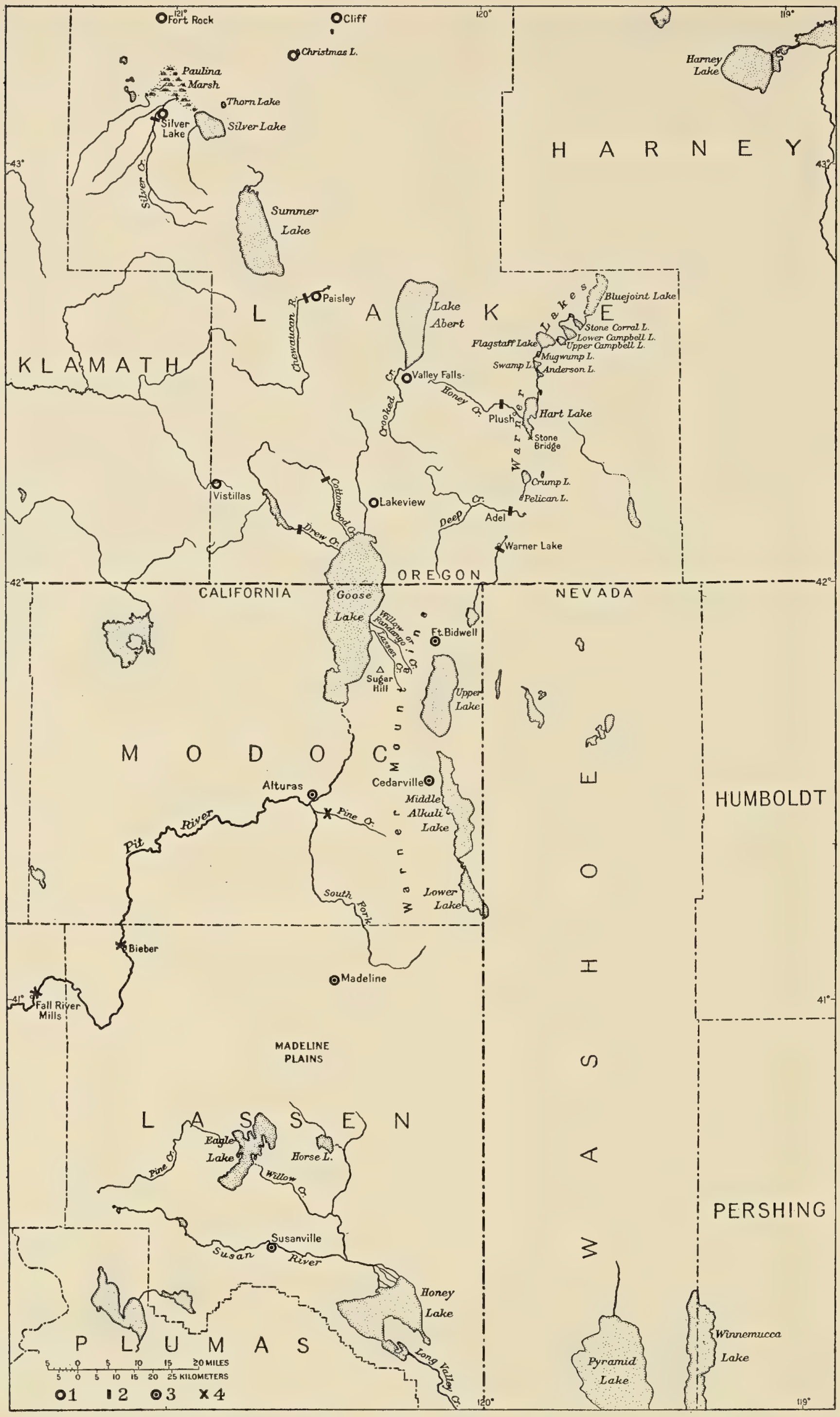

Fig. 2—Map of Lake County, Oregon, and of Modoc and Lassen counties, California, and vicinity. Scale, 1 : 2,000,000. The curves for this region on Plate II are based on records for the rainfall and gauging stations shown on this map by the symbols 1, 2, 3, and 4. (1 and 2) Lake County: (1) rainfall (Pl. II, m; a rainfall station should be added on the Ana River, the northern tributary of Summer Lake); (2) runoff (Pl. II, k, l). (3 and 4) Modoc and Lassen counties: (3) rainfall (Pl. II, p); (4) runoff (Pl. II, n, o). For the gauging station at Ydalpom see Figure 1.

Bluejoint Lake, the northernmost of the chain.[4] About eight feet of this drop occur between Hart and Anderson lakes, third and fourth from the south respectively.

The winter of 1844-45 was rainy in Oregon, and the consequent floods were more destructive than any that followed till November 1861.[5] When Jesse Applegate on July 8, 1846, located the Old South Road to Oregon around the south end of Goose Lake on the boundary between California and Oregon this was a large body of water.[6] The summer of that year was dry and the grass crop poor, which added to the difficulties of the emigrant trains. A cold and early winter followed, bringing unusual amounts of rain and snow and causing great losses of cattle.[7]

Goose Lake is normally a large body of water, 28 miles long and 4 to 10 miles wide, and is fed by many brooks and small rivers. It usually lacks an outlet but on rare occasions overflows southward to the North Fork of the Pit River. When filled to the overflow channel the lake measures about 186 square miles and is 26 or more feet deep over an area of 29 square miles.[8] Most of the deepest area lies south of the state line (Fig. 3). In the autumn of 1914, when the lake stood three feet below the outlet, its water tasted slightly salty and was unfit for domestic and irrigation purposes, though cattle drank it freely and large rainbow trout thrived in the lake.[9]

In 1848 Goose Lake was low.[10] On August 27, 1849, the lake surface was estimated by Delano at 20 by 8 or 10 miles, but the water was alkaline and unpalatable.[11] The route of Delano's trek seems to have crossed an exposed strip of lake bottom along the east side of the basin down to the south end of the lake. Cattle, which were driven that summer from Oregon to Fort Hall (Pocatello, Idaho) by the South Road, found excellent pasturage, suggesting that the precipitation had been heavy during the preceding winter in Oregon, as it is reported to have been in northern California and northern Nevada.[12]

A rainfall graph for Sacramento, San Francisco, and Red Bluff in northern California covering the period 1850-1936 for the sake of brevity is here called the "Sacramento rainfall curve" (Plate I, a). After smoothing, this curve displays a general conformity with the smoothed precipitation curve for Lake County since 1890 and may therefore approximately record the rainfall maxima and minima, their time and prominence, in Lake County between 1850 and 1890. Since this curve during the fifties and sixties well matches the tree growth at Lakeview and since both curves correspond with the fluctuations of the lake levels, the usefulness of the Sacramento rainfall graph as a record for Lake County is further shown, while the value of the tree-growth curve as an approximate measure of the rainfall in the years 1850-70 is also established.

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[4] Whistler and Lewis (1916), 16.

[5] Hines (1859), 334; Bancroft: Oregon (1888), 483; Scott, Vol. 5 (1924), 134. These and most other old data on precipitation, floods, crops, and cattle refer no doubt primarily to western or northwestern Oregon. It is not known to what extent they apply to our region.

[6] Applegate (1921), 25.

[7] *Lake County Examiner,* May 2, 1929; Oliphant (1932), 6.

[8] California . . . : Pit River (1915), 90, 94, Pl. 13.

[9] *Ibid.,* 90.

[10] Burnett (1880), 257.

[11] Delano (1857), 205.

[12] Illustrated history of Plumas . . . counties (1882), 147; *Lake County Examiner,* May 9, 1929; Hulbert (1931), 216.

The winter of 1849-50 was severe, with deep snow in Oregon and heavy precipitation in the Sacramento region.[13] The summer of 1851 was very dry in California, and that of 1852 dry in Oregon.[14] Again during the winter of 1852-53 there was much cold and snowy weather with bad floods.[15] In the middle fifties there may have been an ample water supply in the Lakeview region, for the tree rings are wide for 1854 and 1855. Thereafter, judging from the tree growth and the Sacramento rainfall, the Lakeview precipitation decreased to a moderate minimum about 1858 and then increased to another maximum in 1861 or 1862.

Tradition and history relate that early emigrants bound for Oregon and northern California came out of the Fandango (Willow) and Lassen valleys to the central part of Goose Lake basin and turned southward. After traveling on the exposed lake bottom around the high promontory of Sugar Hill on the east side they turned west, crossing the basin. According to Symons [16] the old road could be distinctly traced in 1877 from the Lassen Pass out into the lake; and it was also clearly visible on a then-submerged peninsula on the opposite shore of the lake. This road, which is shown on the map of the Wheeler Survey of 1877-78,[17] crossed the lake in a southeast-northwest direction between the peninsulas that contract the lake a few miles from its southern end.[18] The lowest point between the peninsulas lies more than 16 feet below the outlet channel. When the lake became completely dry in the summer of 1926 wagon tracks, parts of wagons, ox yokes, sage and willow stumps, etc. were exposed at different places. Mr. Getty of Lakeview on September 12, 1926, photographed wagon ruts at a point lying about ten miles south of the state line, one mile out from the west shore of the lake and fully 20 feet below the outlet sill.[19] These tracks probably crossed the lake a few miles north of the peninsulas mentioned. In 1931 no tracks could be discovered on the dry and sandy lake floor.

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[13] History of the Pacific Northwest, Vol. 1 (1889), 406.

[14] Sargent (1921), 4.

[15] History of the Pacific Northwest, Vol. 1 (1889), 406; Sargent (1921), 4; Horner (1931), 195.

[16] Symons (1878), 1539.

[17] U. S. Geographical Surveys West of the One Hundredth Meridian, Topographical Atlas, Sheet 38 B, reproduced in part in Bowman (1935), 46, Fig. 3.

[18] Fairfield (1916), 4.

The exposed tracks aroused considerable interest in the region, and various attempts were made to determine the date of their formation but without definite success.[20] It is generally believed that the lake was entirely desiccated at the time, the writer having encountered only one person, a farmer near Sugar Hill, who held that only the southern part of the lake was dry. However, there does not seem to be any evidence to warrant belief in complete desiccation. On the contrary, the fact that the emigrants turned southward from the Fandango and Lassen valleys before they crossed the basin, suggests that there was water or moist ground in the lake basin opposite these valley entrances. Since the lake bottom here stands 22 to 25 feet below the outlet and the location of Mr.

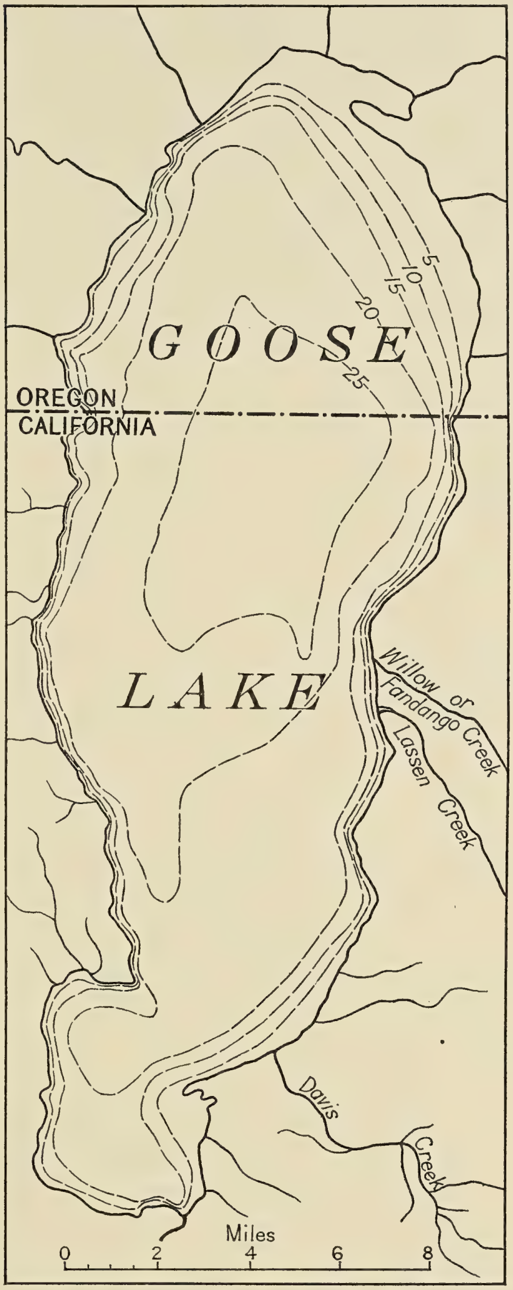

FIG. 3—Bathymetrical map of Goose Lake, California and Oregon. Scale, 1:275,000. The contours show depths in feet, Aug. 20, 1904, when the water surface was one foot below the outlet and at an assumed elevation of 4800 feet. Adapted from Plate 13 in California, Department of Engineering: Report on Pit River Basin, Sacramento, California, 1915.

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[19] One of Mr. Getty's pictures is reproduced in Bowman (1931), 101, Fig. 77; also in Bowman (1935), 47, Fig. 5.

[20] Baker (1929).

Getty's pictures seems to suggest a lowering to at least 20 feet below the threshold, the lake, when smallest, was perhaps some 50 square miles in area. Reliable information describes Goose Lake as extensive though shallow during the late eighteen-forties. In 1854 emigrants traveled on the exposed lake floor around the promontory of Sugar Hill.[21] Considering the historical data, the small tree growth during the forties, the growth maximum in 1855, the Sacramento rainfall, and the lag in the fluctuations of the lake due to its size, it seems probable that Goose Lake was lowest during the first part of the fifties and shallow during the late forties. The several wagon ruts on the lake bottom might therefore have been formed between the late forties and the middle fifties.

An explanation of how the tracks could be preserved under water for some 75 years seems to be given by an observation of my wife in the Upper Lake of the Surprise Valley. Here sun-baked tracks, when submerged by the rising lake, had retained their shape and had been filled with a fine clay, which, turning white and hard upon a later exposure, caused the outline of the ruts to become clearly discernible. In Goose Lake the submerged, water-resistent ruts may, instead, have been filled with silt and sand, which upon exposure was removed by the wind. Then, after a few years, the tracks were completely obliterated by wind-driven sand and silt. Stories of troublesome dust storms were told by the inhabitants to the south, at Alturas.

When Silver Lake, situated 70 miles north-northwest of Goose Lake, dried up in 1889, sagebrush found on the lake bottom showed that this must have been exposed some time before the arrival of the first settlers in 1868, after the Shoshone Indian War.[22] This was probably during the dry period of the eighteen-forties. In 1861 the Paulina Marsh, a few miles northwest of Silver Lake, was found by gold prospectors to be practically a lake, extending almost to the site of the town of Silver Lake.[23] Silver Lake, which in 1908 measured three by six miles,[24] is normally supplied by a small river and by brooks that reach it via Paulina Marsh. The first diversion of the waters of the tributaries was made about 1875. Since 1895 practically all of the summer flow has been taken for irrigation.[25] Under normal conditions Silver Lake is a closed basin, but occasionally it overflows northeastward to Thorn Lake and the Christmas Lake valley. The bed of Silver Lake stands at an average elevation of 4430.5 feet, the lowest point at 4429 feet, the point of outlet to Thorn Lake at 4440.5 feet, and the highwater mark at 4442 feet; hence the depth of the water during overflow is ten or more feet.[26] The water is entirely fresh. The absence of salts may be due, not to the occasional overflow, but to the blowing away of the deposited salts when the lake becomes desiccated or to their being buried beneath silts.[27]

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[21] Powers (1874), 344.

[22] Whistler and Lewis (1915), 41.

[23] *Ibid.*, 17.

[24] Waring (1908), Pl. II.

[25] Whistler and Lewis (1915), 89.

Excessive rains and snows, destructive floods, and bitterly cold periods made the winter of 1861-62 the most disastrous in Oregon history.[28] A deluge of rain began towards the end of November 1861 and continued for several days, inundating all the valleys west of the Cascades and destroying the accumulations of years of industry.[29] East of the Cascade Range the winter was exceptionally severe with very heavy snowfalls and cold spells during which the mercury often fell below −30° F.[30] Rivers were closed for traffic during two months, and fully half of the horned cattle and probably a third of the horses, mules, and hogs perished by drowning, freezing, or starvation.[31]

The Lakeview tree growth and the Sacramento rainfall indicate that precipitation in Lake County decreased from its climax in 1861 or 1862 to a minimum in 1864, then increased to another maximum in 1868, and again decreased to a minimum in 1871. Other data are in agreement. The autumn of 1863 was dry.[32] The winter of 1864-65 was severe in eastern Oregon.[33] That of 1866-67 was very cold and snowy in the Warner valley.[34] The ensuing rise of the rivers and lakes necessitated the building of the famous stone bridge across the valley at the southern end of Hart Lake (one of the Warner Lakes), when Camp Warner was moved during the following summer. According to data collected by Mr. J. E. Stewart the Warner Lakes seem to have been higher in the late sixties than at any other time during the last century.[35] Also Goose Lake expanded exceptionally during the sixties and in 1869, after a storm, overflowed into the Pit River.[36]

In the seventies the Lakeview tree growth and the Sacramento rainfall show less agreement. The tree growth is perhaps a less accurate measure of the precipitation for this period than for the two preceding decades. Precipitation in Lake County probably was somewhat below the average during the first years and rose to a moderate maximum in the latter half of the seventies. The winter of 1871-72 was very cold and snowy, though not so rigorous as that of 1861-62.[37] In the spring Goose Lake extended up to the site of Lakeview, then a meadow covered with water.[38] The winters of 1872-73 and 1874-75 were likewise severe with plenty of snow in the Goose Lake region and other parts of Oregon.[39] During the summer of 1874 Goose Lake was a large body of water with an abundance of fish, said to be trout.[40] The Warner Lakes are reported to have been high about this time.[41] The winter of 1875-76 was snowy, causing a large loss of livestock.[42] In 1877 Goose Lake was rather high.[43] The years 1877-79 were dry in Lake County, according to Mr. L. F. Conn of Lakeview. From 1876 to 1884 the runoff in the Warner valley was considerable, except during two or three years. In 1879 a fish, *Myloleum,* was found in Hart Lake.[44] The water of Lake Abert must have been relatively diluted for some time previous to 1879, for a fish, *Myloleucus formosus,* then lived in the lake.[44] In 1879 Silver Lake was only four feet deep but contained fish. Thorn Lake was dry.[44]

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[26] *Ibid.*, 41, 48, 50, 122; *ibid.* (1916), 33.

[27] Van Winkle (1914), 116.

[28] Horner (1931), 196.

[29] Bancroft: Oregon (1888), 483.

[30] Goulder (1909), 233.

[31] Scott (1924), Vol. 5, 129, 134; Oliphant (1932), 8.

[32] Scott (1924), Vol. 5, 158.

[33] Oliphant (1932), 10.

[34] Illustrated history of central Oregon (1905), 812

[35] Whistler and Lewis (1916), 17, 31-34.

[36] Symons (1878), 1538; Russell (1884), 456.

[37] Oliphant (1932), 10.

The smoothed graphs of the Lakeview tree growth and the Sacramento rainfall match well during the years 1880-85, but seem to suggest less precipitation than actually occurred in Lake County. The curves mostly disagree during the latter half of the eighties, and for one year each, 1886 and 1888, appear to indicate heavier rainfall than seems probable. The winter of 1879-80 was exceptionally severe with great losses of cattle in the Goose Lake region.[45] The following winter also brought heavy precipitation and floods.[46] As a consequence, Goose Lake in 1881 reached its second climax in the memory of white man and overflowed for two hours during a gale from the north.[47] Summer Lake in 1882 had an average depth of less than ten feet. It was strongly saline and did not contain any fish.[48] Having risen six feet since 1879, Silver Lake in June 1882 had a uniform depth of ten feet and was confluent with Thorn Lake.[49] No records seem to have been made of the fluctuations of Lake Abert; but, if the salinity of the analyzed water samples be taken as a guide, the lake was high in September 1887, the salt content then being 3.8 per cent.[50] In 1887 Goose Lake stood a few feet below the outlet threshold.[51] About 1885 a series of dry years began in the Warner valley, culminating in 1889. In the fall of

[38] Illustrated history of central Oregon (1905), 844.
[39] Oliphant (1932), 12; Illustrated history of central Oregon (1905), 818.
[40] Powers (1874), 342-344.
[41] Free (1914), 26.
[42] *Lake County Examiner,* June 19, 1924.
[43] Symons (1878), 1538.
[44] Cope (1889), 975.
[45] *Lake County Examiner,* June 19, 1924; June 13, 1929.
[46] Scott (1924), Vol. 5, 134; Oliphant (1932), 13.
[47] Russell (1884), 457.
[48] *Ibid.,* 455.
[49] *Ibid.,* 454, 456.
[50] Van Winkle (1914), 119.
[51] Biddle (1888), 479.

that year Crump Lake was restricted to a small area on the western margin of its basin, and Hart Lake was small; while Bluejoint, Flagstaff, and the intervening lakes no doubt had gone dry before this.[52] Summer Lake shrank little, if at all, in the dry period 1887-89.[53] Silver Lake subsided during the latter half of the eighties and dried up in 1889.[53] Throughout Nevada, northern California, and other regions of the West, as well as in Lake County, the drought was abruptly broken during the winter of 1889-90 by heavy rains and snows, which together with accompanying floods and unusually low temperatures caused great losses of livestock and other property.[54] The following season the rivers swelled and the lakes rose considerably. Silver Lake and Thorn Lake were filled, and water overflowed into the Christmas Lake valley.[55]

The Period 1891-1909

Since 1890 records have been kept of the weather conditions in Lake County. The precipitation curve here presented (Plate II, m) is based on the data for the stations Lakeview (1891-), Vistillas (1910-17), Valley Falls (1911-), near Paisley (1907-19), Paisley (1926-), the Ana River (1910-16), Christmas Lake (1910-16), Cliff (1908-16), Silver Lake (1898-1924), and Fremont (Fort Rock) (1910-), which lie at elevations of between 4200 and 5280 feet. The heaviest precipitation, 19.3 inches, occurs at Vistillas, the highest station; and the lightest, 7.4 inches, at the Ana River. The mean precipitation at all the stations is 10.6 inches. At most stations the precipitation has one or two maxima in winter, a secondary maximum in spring, mostly in May, and invariably a minimum in August. The single winter maximum lasts from November or December to February. The two winter maxima prevail in November and January, or in November and in January and February. The stations Christmas Lake and Cliff have maxima in June, secondary maxima in November and January, and minima in August.[56]

The precipitation was considerably above the normal in 1890-97. The Warner Lakes were high in 1895.[57] Goose Lake perhaps overflowed during one of these years rather than during the very dry year of 1898, as stated by Harding,[58] unless his information is supported by contemporary records. In 1898 another series of dry years began, which lasted until 1903, when Bluejoint, Stone Corral, Lower Campbell, and probably Upper Campbell lakes in the Warner valley became dry.[59]

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[52] Whistler and Lewis (1916), 31, 32.

[53] Waring (1908), 38.

[54] Scott (1924), Vol. 5, 134; Oliphant (1932), 16; *Lake County Examiner,* June 19, 1924.

[55] Whistler and Lewis (1916), 33.

[56] For a general review see Wells (1922).

[57] Whistler and Lewis (1916), 32.

[58] Harding (1935), 90.

[59] Whistler and Lewis (1916), 32.

Also Lake Abert and Summer Lake may have receded during this period of drought, for in October 1901 and in 1902 their salt contents were relatively high.[60] The winter of 1903-04 was generally rainy and snowy in Lake County, and on August 20, 1904, Goose Lake stood but one foot below the overflow channel.[61] Silver Lake filled in the spring, and it overflowed into Thorn Lake at least as late as September 17. In January 1905 its water surface was at 4440.8 feet; and Silver and Thorn lakes were united by a channel varying between 50 and 200 feet in width.[62] In March and April the water level stood at 4441 feet. During the years 1905 and 1906, which, according to the graph, had an average rainfall in the county, Bluejoint Lake, farthest of the Warner Lakes from the tributaries, dried up. The seasons 1907 and 1909 were wet in the Warner valley, and the lakes were probably nearly as high as in 1910 when records of stage were begun.[63] At the rainfall stations represented in our graph the precipitation was very heavy in 1907 but was a little below the average in 1908 and 1909. About 1907 Lake Abert was a large body of water. The winter and spring of 1908 were dry in central Oregon.[64]

THE PERIOD AFTER 1909

Since 1909 the stream flow has been systematically measured in Lake County. The runoff curve here given (Plate II, k) is based on the records of the following gauging stations: Drew Creek near Lakeview (Station No. 813), 1909-30; Cottonwood Creek near Lakeview (Station No. 818), 1926-; Twentymile Creek near Warner Lake P. O. (Station No. 916), 1909-19; Deep Creek at Adel (Station No. 919), 1909-16, 1918-19, 1921-23; Honey Creek near Plush (Station No. 914), 1910-14; Chewaucan River near Paisley (Station No. 924), 1909-21, 1925-; and Silver Creek near Silver Lake (Station No. 943), 1909-27, 1929-.[65] All the gauging stations occur below some water diversions. The runoff is greatest in spring, usually in April, and smallest in the late summer, mostly in August.

The averages of the rainfall and the runoff graphs of Lake County are not comparable, because since 1910, when runoff measurements were begun, precipitation and stream flow have been much smaller than during the period 1890-1909. Except for 1910, when the runoff was at a peak whereas the measured rainfall was near the average, the two curves show contemporary maxima and minima and the annual fluctuations trend normally in the same directions. However, the curves have different general trends, that of the rainfall being nearly horizontal, that of the runoff undergoing a broad decline towards the present, chiefly, no doubt, because of increasing diversions. To eliminate the effect of the diversions the adjusted runoff curve has been given the trend displayed by the rainfall graph by the method described in the Introduction. Rainfall and runoff were of markedly different relative amounts in 1910, 1911, 1914, 1917, 1920, 1921, 1923, 1925, and 1930.

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[60] Van Winkle (1914), 119-120.

[61] California . . . : Pit River (1915), 90.

[62] Whistler and Lewis (1915), 48, 50.

[63] *Ibid.* (1916), 32.

[64] Bowman (1931), 96.

[65] The data up to 1924 are compiled in *Bulletins* No. 4 and 7 (1915, 1925) issued by the Oregon State Engineer. Later records are to be found in the *U. S. Geological Survey Water-Supply Papers* (Surface Water Supply of the United States, Parts 10 and 11), Nos. 610, 611, 630, 631, 650, 651, 670, 671, 690, 691, 705, 706, 720, 721, 735, 736, 750, 751, 765, 766, 790, 791, for the period 1925-1935.

During the period 1910 to 1916 the precipitation in the region was evenly distributed among the years and a little above the average. The runoff was very large in 1910, large in 1911, and average in 1912 and 1913. In 1910 the Warner Lakes stood comparatively high, Crump Lake reaching 2½ feet above its overflow channel to Hart Lake. However, as the runoff decreased, the water levels gradually subsided during the next three years.[66] In February 1912 Lake Abert and Summer Lake may have been rather high, for their salt contents were low.[67] Silver Lake in 1912 stood five feet below the high-water mark, or at an elevation of 4437 feet.[68] In 1914 the streams carried large quantities of water. Consequently Goose Lake in August of that year stood only three feet below the outlet sill,[69] and the Warner Lakes with one exception underwent a small rise.[70] However, Bluejoint Lake, farthest north, became desiccated and has remained dry ever since except for some water in the spring. Also Siver Lake receded in 1914, standing on November 2 at an elevation of 4435.5 feet.[71] Upon a deficient runoff in 1915 the lake subsided to 4434.1 feet on July 22 and to 4432.8 feet in October, when its greatest depth was only four feet and the average depth a little over two feet.[72] In March 1915 Thorn Lake was reduced to a small pond, but it contained a fish resembling the whitefish.[73] The Warner Lakes were again rather low in the dry year of 1915.[74] Thus Crump Lake stood two feet below the outlet channel and Flagstaff Lake four feet below its normal level. In 1916 the runoff was large, and it increased in 1917 although the measured rainfall decreased considerably.

During the years 1918-20 both rainfall and stream flow had marked minima. Silver Lake became totally dry and remained so through 1936, owing in part to increased diversion of the waters of the tributaries. Beginning in 1915 crops were planted on the partly exposed floor of this lake, and for some years large harvests were obtained.[75] In 1924 the lake basin formed a great meadow where cattle grazed,[76] but subsequently the lake floor grew drier, changing into a desert. In 1931 it was hard and firm, where not consisting of sand, and largely overgrown with the ordinary desert shrubs.[77] During this dry period Stone Corral Lake and the two Campbell lakes may also have dried up. They are the second and fourth from the north of the northern Warner Lakes, which are said to go dry successively from north to south.

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[66] Whistler and Lewis (1916), 16, 34.
[67] Van Winkle (1914), 114-120.
[68] Whistler and Lewis (1916), 33.
[69] California . . . : Pit River (1915), 90.
[70] Whistler and Lewis (1916), 17.
[71] *Ibid.* (1915), 50.
[72] *Ibid.* (1916), 33.
[73] *Ibid.* (1915), 49.
[74] *Ibid.* (1916), 17.

The drought of 1918-20 had important consequences and taught a severe lesson. Encouraged by the comparatively heavy precipitation beginning in 1904, the enlarged Homestead Act of 1909, intensive advertising, cheap land, and high prices of wheat and other products, settlers had come into the region in great numbers, many of them to try dry farming.[78] The hazard of drought was not given sufficient consideration, and the first dry spell proved the impossibility of the attempted colonization and started an exodus that continued till 1926 or later, leaving hundreds of abandoned homesteads.[79]

The winter of 1920-21 was very snowy, causing losses of sheep, and was followed by the second largest runoff during the last 27 years. During the next two years the precipitation remained about the same, while the stream flow underwent a decided decrease. In 1923-24 the precipitation dropped to 45 per cent of the normal and the runoff to still less, making this the driest year of record in Lake County. The hay crop was smaller than ever before. In the beginning of September the leaves on the trees dried and fell off.[80] In August Lake Abert became desiccated except for a few small pools fed by springs and a small area on the east side supplied by Poison Creek.[81] Flagstaff Lake, fifth from the north of the Warner Lakes, became dry and remained so in 1934, although it held an increasing quantity of water in 1935 and 1936. Hart Lake, another of the Warner Lakes, which at normal level is 6 feet deep in the southern part and 14 feet deep to the north, also dried. The small Pelican Lake in the southern part of the Warner valley was probably dry. The winter of 1924-25 was severe and snowy, and since there was little stored feed many cattle died.[82] The summer of 1926 was exceptionally dry in Lake County and next to 1934 the warmest on record in Oregon. In July or August the large Goose Lake, whose fluctuations between 1914 and 1926 do not seem to be recorded, dried up.[83]

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[75] *Ibid.* (1915), 41.

[76] Smith and Young (1926), 221.

[77] See Bowman (1931), 106, for further data.

[78] *Ibid.*, 93-110.

[79] Smith and Young (1926), 241, 252.

[80] *Lake County Examiner,* June 19, July 3, Aug. 14, Sept. 5, 1924.

[81] *Ibid.*, June 14, 1924.

[82] Bowman (1931), 102.

[83] *Lake County Examiner,* July 15, Sept. 2, 1926.

In 1927 and 1928 the water supply was again plentiful, and in April of the latter year the streams in Lake County were running bank full, with reservoirs and lakes rising.[84] Goose Lake contained water throughout the summers. The next year, however, was the third driest that had been experienced in the region [85] up to that time, and Goose Lake again dried and did so every summer to and including 1934. Hart Lake also probably became dry. During the year of 1929-30 precipitation was about average at the rainfall stations, but the measured stream flow was small, suggesting that precipitation must have been deficient in the mountains. The year 1931, the third dry year in succession, with a precipitation of only 56 per cent of the average and a runoff relatively smaller still, was almost as dry as 1924. Having been very low during most of the summers since 1924, Lake Abert in October 1931 was at about the same level as in August 1924. Near the east side not far from the south end spread a sheet of water about half a mile wide and a few miles long, and on the west side, also to the south, there were small patches of shallow water. The stream bed at the southern end of the lake was completely dry. Summer Lake, which has been going down since about 1920, in October 1931 was lower than at any previous time since the white man occupied the region. It consisted of a sheet of water two miles or more wide extending along the central axis of the basin from the northern end to two or three miles from the southern end. On each side a white floor was exposed two miles or more out from the normal shore. Hart Lake was probably dry. Pelican Lake, which dried up almost every summer during the period 1918-34, did so in 1931 during the middle of July. In October 1931 Crump Lake consisted of a remnant on the western side of its basin a mile and a half long and on an average 200 yards wide. The drought reached its culmination in 1931.

In 1932 the precipitation and runoff were about normal, but in 1933 and 1934 the water supply was subnormal. It was adequate in 1935 and 1936. As stated, Silver Lake has been dry every summer since about 1918, and Goose Lake was dry during the summers of 1929-34. In 1933 and 1934 all the Warner Lakes were desiccated with the exception of Crump Lake, which has never been dry since the white man came to the region. However, the latter was extremely low in the late fall of 1934. Lake Abert, which is in part fed by springs in the lake, has not completely dried up in historic times, although at no time during the years 1931-34 did it contain enough water to cover the entire floor. Since 1935 Goose Lake, the Warner Lakes, and Lake Abert have held an increasing amount of water and at present (July 1937) are perhaps two-thirds full. Similarly, Summer Lake, fed from springs through

[84] *Ibid.*, April 19, 1928.

[85] *Ibid.*, Sept. 5, 1929.

the Ana River, held some water through the latest and other droughts. It is doubtful whether some of the lakes would have become desiccated during the recent droughts had not their tributaries been diverted for irrigation purposes.[86]

The chief rainfall fluctuations of the region since 1846 are summarized in the " total " plot (Plate II, g).

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[86] The writer is indebted to Messrs. J. C. Scharff and W. O. Harriman of Lakeview for data on the lakes during the years 1932-34 and to Mr. G. H. Canfield of Portland for unpublished data on the runoff.

CHAPTER II

THE GREAT BASIN REGION OF NORTHEASTERN CALIFORNIA: MODOC AND LASSEN COUNTIES

The Period Before 1889

The region discussed in this chapter comprises Modoc and Lassen counties in the northeastern corner of California. During the first half of the last century the local water supply, judging from the tree growth at Susanville (Plate I, c), was mostly above the normal, but it had marked minima about 1829 and 1844 and smaller minima in 1815 and 1823. Indian tradition tells of a terrible flood about 1805, and the annals of the Hudson's Bay Company record heavy storms and floods during the year 1818 in what is now Plumas County, just south of the region under consideration.[87] During the winter of 1848-49 deep snows fell in the mountains of Plumas County,[88] and the tree growth of the following season was above the average at Susanville. However, in August of the same summer "Hot Spring Lake" was entirely dry.[89] "Hot Spring Lake" is either Upper Lake or Middle Alkali Lake, probably the former, one of the shallow playa lakes of the Surprise Valley which are supplied by numerous brooks rising in the beautiful Warner Mountains (see Fig. 2, p. 8, above).

After smoothing, the precipitation graph for Sacramento, San Francisco, and Red Bluff, used in the previous chapter and called the "Sacramento rainfall curve" (Plate I, a), matches rather well the smoothed rainfall graph for Modoc and Lassen counties since 1889 (Plate II, p).[90] Even the unsmoothed curves correspond in most respects. The Sacramento graph therefore may be used as an indicator of the general fluctuations of the rainfall in the present region during the time 1850-88. Since the tree growth at Susanville during the eighteen-fifties and sixties fluctuates in general harmony with the Sacramento rainfall and with the levels of Honey Lake, the Susanville ring curve may also represent a fair record of the major variations of the rainfall of 1850-70.

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[87] Illustrated history of Plumas . . . counties (1882), 143; Grunsky (1930), 290.

[88] Illustrated history of Plumas . . . counties (1882), 147.

[89] Delano (1857), 202, 205.

[90] There are rainfall data for Fort Bidwell from 1866 through 1893. However, the annual fluctuations as well as the actual amounts of precipitation as recorded for these years are in many cases enormous in comparison to what they have been since 1911, when rainfall measurements were resumed. The discrepancy between the record of continuously deficient rainfall in 1872-76 and Russell's statement (1884, 457) that the adjacent Upper Lake, although dry during the summers of 1872 and 1873, otherwise contained water throughout the seventies, could be due to Russell's misinformation. But there is no such explanation for the following discrepancy. Middle Alkali Lake was quite dry in September 1887, the other two lakes were nearly dry (Biddle, 1888, 481), and there was an increasing drought in 1888 and 1889 according to old settlers. In spite of this, the Fort Bidwell record indicates rainfall well above the average during the years 1884-87 and 1889, and only slightly below it in 1888. For these and other reasons the Fort Bidwell rainfall record 1866-93 is not here used.

From the Susanville tree growth and the Sacramento rainfall it appears that the precipitation in Modoc and Lassen counties increased from the middle forties till about 1853 and then diminished till about 1859. Other data agree with this. The winter of 1849-50 was wet in Plumas County, and that of 1852-53 was marked by disastrous floods in all California.[91] On July 5, 1854, Honey Lake, a playa lake of variable extent supplied largely by the Susan River but also by Long Creek as well as by brooks and springs, measured about ten miles from northwest to southeast and stood a few feet below an old shore line.[92] This is one of the highest levels it has reached since the white man came to the region. On the other hand, in the fall of 1859 the lake was entirely dry, and its bed sufficiently firm to support teams.[93]

After the minimum in 1859 the precipitation appears from the data at hand to have increased till 1862, then decreased till 1864, again increased till 1868, and thereafter diminished till 1871, undergoing marked fluctuations. The winter of 1859-60 was harsh. The snow was not extremely deep, but it came early and stayed till late in the spring, and the cold was steady and severe. Persistent fogs produced so much frost on the grass that numbers of cattle died from starvation.[94] The winter of 1861-62 was very rainy and snowy with great floods in Plumas County.[95] The winter of 1863-64 was extremely dry in the Susan Valley, there being one storm with light rain. Although some rain fell in the following spring and summer, it was entirely insufficient, and little or no crops could be raised on land that was not irrigated.[96] Probably in 1864 Honey Lake again became desiccated (not in 1863 as settlers informed Symons in 1877[97]). In November 1865 destructive floods occurred in the region of Honey Lake.[98] In April 1867 the lake rose rapidly and during the following summer was very high and large, covering some 90 square miles. After the stormy winter of 1867-68 the water stood higher than at any time in the white man's memory, submerging and destroying hay and farm land for miles about the shores.[99] In April 1868 Madeline Plains, 40 miles north of Honey Lake,

[91] Illustrated history of Plumas . . . counties (1882), 143.

[92] Beckwith (1855), 47.

[93] Russell (1885), 56; Fairfield (1916), 186.

[94] Fairfield (1916), 186, 207.

[95] Illustrated history of Plumas . . . counties (1882), 143.

[96] Fairfield (1916), 334.

[97] Symons (1878), 1537.

[98] Fairfield (1916), 388.

[99] Illustrated history of Plumas . . . counties (1882), 384; Russell (1885), 55; Fairfield (1916), 446, 465.

lay under water for seven or eight miles.[100] Horse Lake, a small playa lake 25 miles north of Honey Lake, was so high in 1868 that it overflowed into a channel some ten feet above the usual lake level and discharged into Honey Lake.[101]

During the eighteen-seventies there is neither a decided conformity nor a discrepancy between the smoothed graphs of the Sacramento rainfall and the Susanville tree growth. Both curves are probably fair records of the main variations of the precipitation, though less reliable than for the two preceding decades. The rainfall in the region seems to have been a little below the average during the first half of the seventies and a little above during the last part. Upper Lake in Surprise Valley dried in the summers of 1872 and 1873, and Lower Lake at about the same time.[101] (If the Fort Bidwell rainfall record is correct, the desiccation occurred instead during 1875 and 1876.) Upper Lake left a mud plain with a saline efflorescence, and Lower Lake deposited a large amount of fairly pure salt. In June 1877 Honey Lake had an average depth of 18 inches and was strongly alkaline.[102] Horse Lake also was low and alkaline in the same summer, and in 1878 and 1879 it was entirely dry.[103]

During the eighties the graphs of the Sacramento rainfall and the Susanville tree growth show more disagreement than conformity. There is little from which to evaluate the curves during the first four or five years of the decade. Heavy rains and snows in Plumas County in 1881 resulted in floods that caused great damage.[104] In 1882 the average depth of Honey Lake was 18 inches, and the greatest depth 4 feet.[105] All the five years 1885-89 were dry at Susanville.[106] The precipitation in the region may have been decidedly less than the Sacramento curve would suggest in 1886 or than the tree growth would indicate for 1885-87. After a general subsidence during the seventies and eighties Honey Lake became almost dry in 1888 and quite so in 1889.[107] Middle Alkali Lake in the Surprise Valley was desiccated in September 1887, and Upper and Lower lakes were nearly so.[108] Farmers inform me that the summers 1888 and 1889 were increasingly dry in the Surprise Valley, though not comparable to 1931.

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[100] Fairfield (1916), 453.

[101] Russell (1884), 457.

[102] Symons (1878), 1537.

[103] *Ibid.,* 1538; Russell (1884), 457.

[104] Illustrated history of Plumas . . . counties (1882), 143.

[105] Russell (1885), 56.

[106] Fairfield (MS).

[107] Fairfield (1916), 465.

[108] Biddle (1888), 481.

The Period 1889-1903

Since 1888 the precipitation has been measured in Modoc and Lassen counties. The rainfall curve presented (Plate II, p) is based on the data of the stations Susanville (1889-1918, 1928-), Madeline (1909-23, 1931-), Alturas (1905-19), Cedarville (1895-), and Fort Bidwell (1912-). The stations range in elevation from 4195 to 5270 feet. The precipitation is least, 12.3 inches, at Alturas and greatest, 20.1 inches, at Susanville. The annual average is 15.3 inches. The bulk of the precipitation occurs during the months November to March, with maximum in January. Cedarville and Madeline have faint secondary maxima in May. The rainfall is insignificant during July and August.

The progressive drought of 1885-89 in the region was broken in the winter of 1889-90, which brought first a great deal of rain and then 3⅓ feet of snow in the Susan Valley. As the snow melted, Honey Lake filled almost to the highest beach.[109] During the following years the precipitation fluctuated considerably, diminishing gradually but as a whole remaining well above the average. The winter of 1892-93 was rainy and snowy in the Susan Valley and was followed by high floods. In 1898 the precipitation suddenly dropped to a minimum. The spring and autumn of that year were exceedingly dry, and the summer was hot.[109] The winter of 1898-99 brought little snow in the mountains. Subsequently the rainfall, though marked by great fluctuations, slowly increased to a maximum in 1907. In 1902 Honey Lake was very shallow, and in 1903 it dried up.[110]

The Period After 1903

For the period after 1903 an almost continuous record of the stream flow in this region is available. The curve given (Plate II, n) represents the average of the discharge of Pine Creek near Alturas (1919-31) and of the Pit River near Bieber (1904-08, 1922-31), at Fall River Mills (1921-), and at Ydalpom (1911-). The runoff graph shows a certain conformity with the rainfall curve, if its greater fluctuations and greater general decline, probably due to diversions, are disregarded. The most striking discrepancy is the relatively heavy rainfall but small discharge in 1925. Noteworthy, too, is the relatively greater runoff in 1921.

Precipitation both at the meteorological stations and in the mountains was heavy in 1904, 1906, and 1907 but well below the normal in 1905 and 1908. Honey Lake again contained water in 1904.[111] A downpour on March 16, 1907, caused a devastating flood in the Susan Valley. During the spring Honey Lake filled to one of its highest observed levels.[111]

[109] Fairfield (MS).

[110] Lippincott (1904), 114.

[111] Fairfield (MS).

During the period 1909-13 the precipitation fluctuated between somewhat above and somewhat below the average and then rose to a small maximum in 1914. About 1910 Upper Lake in the Surprise Valley is reported by settlers to have been some three feet deep throughout the summers. In January 1911 there came eight feet of snow in one week at Susanville; and on July 4 there was more snow in the surrounding mountains than ever before seen at that time of year. The winter and spring of 1913 were dry, but July had an exceptional number of cloudbursts.[111] In the summer of 1914 Honey Lake was somewhat above its normal level.[112] Beginning in 1915 the rainfall and runoff on the whole decreased to a minimum in 1918-20. During the summer of 1915 Upper Lake dried, and it has done so nearly every summer since. In January 1916 more snow fell at Susanville than during any previous January known to residents there. The month of January 1918, on the other hand, was perhaps the driest and warmest January on record at Susanville, while September was the wettest September for some 70 years.[113] The inhabitants report that the summer of 1918 was rather dry in the Surprise Valley.

From a minimum in 1920 the precipitation and runoff suddenly increased to a marked maximum in 1921 and then dropped to a minimum in 1924. On May 12, 1922, Honey Lake was " well filled up." [113] Middle Alkali Lake is reported by settlers to have become desiccated about 1923, Honey Lake in 1924. Since then these lakes have contained a little water in the spring but have dried every summer, including that of 1936. In 1925 the precipitation was well above but the runoff below the average. Upper Lake that year contained more water than usually of late. The water supply was small in 1926 but ample during the following year. It then diminished to a minimum in 1931, was somewhat subnormal in 1932, very low in 1933 and 1934, and a little above the average both in 1935 and 1936.[114] If the fluctuations are disregarded, the water supply underwent a decided general decrease from 1907 to 1931. In 1931 the rainfall was 55 and the stream flow less than 50 per cent of the normal amount. This was the driest year since records have been kept and probably since the region was settled by the whites. It marks the turning point in the recent drought. In September 1931 no water was encountered even at a few feet below the dry surface bed of Honey Lake. Horse Lake was dry in the autumn of 1931 and had probably been so for several years, for most of its bed was covered with grass. The Surprise Valley lakes were also desiccated, their bottoms forming cream-colored, vegetationless clay flats. All of these lakes have dried up every summer during the years 1932-36, according to

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[112] Guernsey (1915), 2309.

[113] Fairfield (MS).

[114] Unpublished data on runoff kindly supplied by Mr. H. D. McGlashan of San Francisco.

Mr. Marc W. Edmonds of Susanville, but the water lasted much longer in 1936 than it had during a number of years previously.[115]

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[115] Eagle Lake, a body of water dammed by a lava flow across the course of Willow Creek 15 miles north of Susanville, has been studied in some detail by Harding (1935, 88). According to the U. S. Land Survey map of 1875 the lake then stood at 92 feet above a local datum plane. Harding has approximately determined other elevations of the lake for the time 1875 to 1915, after which there are gauge records. In 1890 the elevation was the same as in 1875, in 1900 it was 100 feet, in 1909 about 108, in 1915 about 107, and in 1917 about 109 feet, the highest recent stand. Since 1917 the levels have become lower. Since 1924 the lake has been tapped by a tunnel to Willow Creek. In 1934 it stood at about the 75-foot level. With the sinking of the water many stumps of submerged trees have been exposed: several at the 100-foot level, a few at 90 feet, and one at 82 feet. The last, whose root system was well wedged among rocks, had about 100 growth rings, and one stump at the 99-foot level had 245 rings. " These records show that Eagle Lake has been continuously higher since 1860 than it was from 1760 to 1860, and that it reached higher stages from 1895 to 1925 than it had since at least 1650, or for 250 years." They also indicate a rise of ten or more feet between 1850 or 1860 and 1875.

The sources of Pine Creek, the only large tributary of Eagle Lake, are less than a mile from those of the Susan River, the main feeder of Honey Lake. The seasonal runoff in these streams may therefore undergo similar fluctuations, and, with undisturbed conditions, the lakes should do the same. Actually, Honey Lake has fluctuated in harmony with the known precipitation of the region, but this has not been the case with Eagle Lake. The moistest times since 1850 have been 1868, 1890-93, and 1904-07, and since 1907 the measured rainfall and runoff have on the whole decreased, while the highest recent stand in Eagle Lake was recorded in 1917. The fact that from 1801 to 1821 a thicker wood mantle was formed in the Susanville trees than during any two later decades prevents us from concluding from the stump at the 82-foot level that the precipitation from 1760 to 1860 was continuously light and much smaller than it has been since 1860. In short, the levels of Eagle Lake cannot be used as a basis for conclusions about the rainfall before 1850. A reasonable explanation of this controversial problem was given the writer in 1931 by Mr. G. N. McDow, president of Lassen County Abstract Co., Susanville, who expressed the opinion that the rise of Eagle Lake was due to a closing of its subterranean outlet about 1890 by an earthquake.

CHAPTER III

THE TRUCKEE-CARSON-WALKER REGION, WESTERN NEVADA

THE PERIOD BEFORE 1871

Historical and traditional data relating to weather and its manifestations are scanty for western Nevada before 1870. However, as we have seen, weather records have been kept since 1849 at Sacramento and San Francisco, directly west of the region. The rainfall graph for these stations and for Red Bluff, the curve here called the " Sacramento rainfall graph " (Plate I, a), shows after 1871 a fair correspondence with the precipitation curves for the region (Plate I, i, j), except that its main maxima are less pronounced. Furthermore, since the Sacramento rainfall curve before 1871 agrees with the available information on precipitation and lake levels in western Nevada, it may be used as an approximate indicator of the rainfall fluctuations there during the period 1850-70. On the other hand, the Susanville tree growth (Plate I, c) does not present sufficiently detailed agreement with the historical and traditional data for western Nevada to warrant our drawing conclusions from it in regard to that region.

The Sacramento rainfall and other miscellaneous records for California, which may be applicable to western Nevada, indicate a precipitation maximum about 1850, a minimum in 1851, another maximum in 1853, and a minimum in 1857 or 1858. Thereafter, judging from the Sacramento rainfall and Nevada data, the precipitation in western Nevada attained a maximum in 1862, abruptly dropped to a minimum in 1864, increased to another maximum culminating in 1867 and 1868, and again decreased to a low minimum in 1871.

In January 1844 Pyramid Lake stood at an elevation of about 3860 feet, as determined by Harding[116] from Frémont's[117] account and sketches. In the fall of 1846 snow began falling in the Sierra Nevada three or four weeks earlier than usual and accumulated to exceptional depths. The blizzard of October 28 trapped a party of emigrants at Donner Lake, three miles east of Summit, California, and 42 persons perished from exposure and starvation before the last surviving members were rescued in April 1847.[118] The winter of 1848-49 brought heavy precipitation which caused large floods in the Sacramento and American

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[116] Harding (1935), 88.

[117] Frémont (1845), 217.

[118] Bryant (1848), 250; Angel (1881), 27; Lewers (1899).

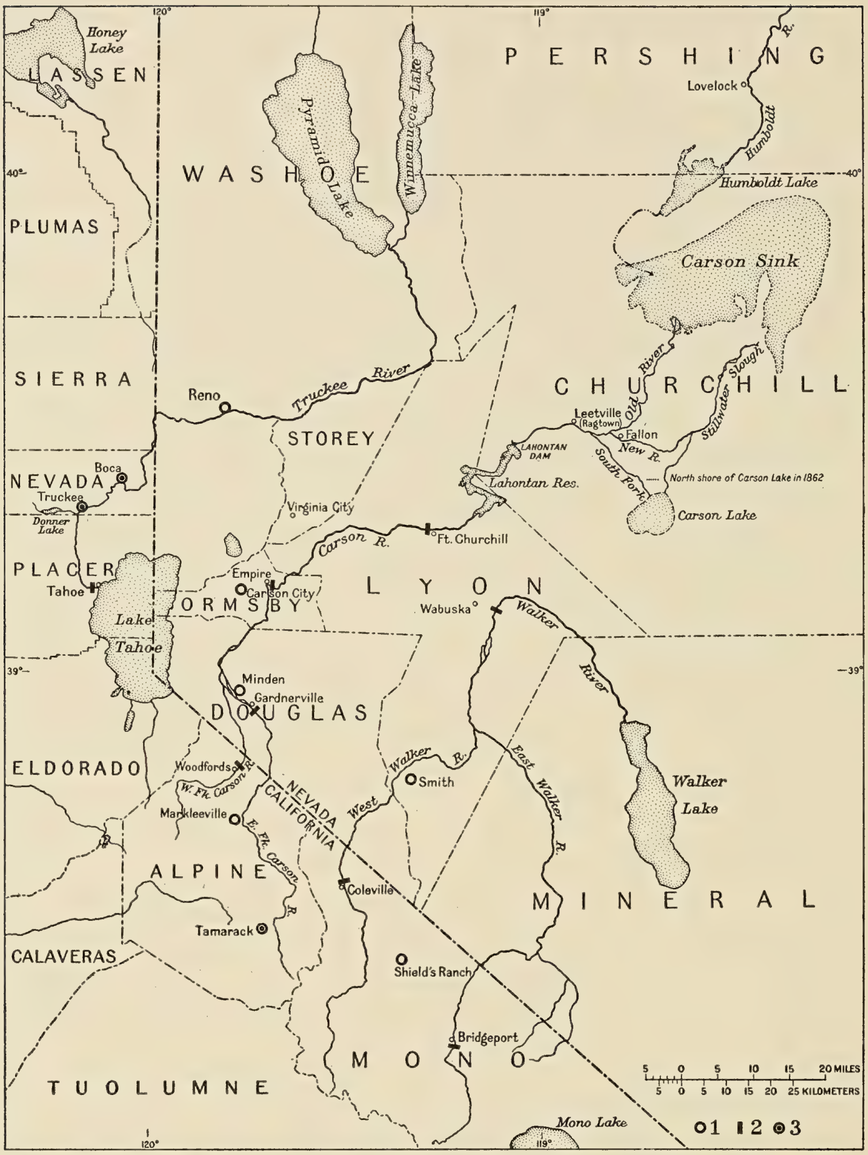

Fig. 4—Map of the Truckee-Carson-Walker region, Nevada and California. Scale, 1: 1,735,000. The curves for this region on Plate I are based on records for the rainfall and gauging stations shown on this map by the symbols 1, 2, and 3. (1) Reno rainfall (Pl. I, i); (2) Truckee-Carson-Walker runoff (Pl. I, g, h); (3) Truckee rainfall (Pl. I, j).

rivers.[119] The winter of 1849-50 was rainy, that of 1850-51 exceptionally dry.[120] Again in 1852-53 there were disastrous floods in all parts of California.[121] The summers of 1856 and 1857 were droughty in California with injurious effects upon agriculture.[120] During the winter 1857-58 but little snow fell in western Nevada.[122] The next winter, on the other hand, was severe with five to six feet of snow in Carson City and environs.[123] The winter of 1859-60, with snow that came early and stayed late, was one of the severest in the history of the Great Basin, so that numbers of Indians and domesticated and wild animals died from cold and starvation.[124] In December 1861 there was an exceptionally heavy snowstorm in western Nevada. When the snow was five to six feet deep in Virginia City and the Carson valley a warm rain set in, causing, during the last days of 1861 and the first of 1862, the most terrific flood ever experienced in the Carson and Walker valleys. The rushing waters filled mines and tore away mills, bridges, river banks, and trees. Water-carried silt completely covered and obliterated the burying ground at Ragtown, now Leetville, eight miles west of Fallon.[125]

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[119] Tyson (1850), 57.

[120] Bancroft: California (1890), 15.

[121] *Ibid.*, 16; Illustrated history of Plumas . . . counties (1882), 143

The flood of 1861-62 had other effects. It deepened the north fork of the Carson, called the Old River, which thereafter diverted most of the water north into Carson Sink. Previously, the Carson River had largely emptied via the South Fork into Carson Lake. The overflow of this lake was carried by the Stillwater Slough north into Carson Sink. After the widening of the Old River, the Stillwater Slough became sluggish or stagnant but at times carried water in the reverse direction, i. e. from the Sink south into the Lake. To avoid overflow during the spring rush of waters the ranchers cut the south bank of the Old River about three miles below the bifurcation and allowed the excess water to escape onto the desert. During a flood in 1867 or 1869 this overflow water cut a channel in the light soil, and the stream discharged eastward into Stillwater Slough. This is the New River (incorrectly called " Old River " on the Carson Sink quadrangle, 1 : 250,000, of the U. S. Geological Survey's topographic map).[126]

A somewhat different account of these events was given to the writer by Mr. G. W. Likes, County Clerk at Fallon. According to Mr. Likes, all the water of the Carson discharged during the early fifties through the Old River into Carson Sink. After a natural dam had been formed in this branch, the bulk of the water was for several years diverted through the South Fork into Carson Lake. During the flood in 1862 the Old River was reopened, and at the same time a new channel, the New River, was formed when the floodwater widened a ditch. The water then flowed in the Old River, the South Fork, and the New River till conditions were changed by the systematic use of the waters for irrigation.

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[122] Angel (1881), 493.

[123] *Ibid.*, 61, 551.

[124] *Ibid.*, 148, 493; Wren (1904), 48, 263; Hazlett and Randall (1921-1922), 25.

[125] Angel, etc. (1881), 166, 364, 406; Stewart (1908), 142; Davis (1913) 791; Hazlett and Randall (1921-1922), 40.

[126] Russell (1885), 43, 44, 68, 137; Strahorn and Van Duyne (1909), 7, 8.

Because only part of the water was stored or diverted for irrigation in the sixties and seventies, Carson Sink received in winter and spring a considerable amount of water both through the reopened Old River and through the Humboldt River; and during these decades it was a large lake, measuring some 15 by 20 miles.[127] Carson Lake in 1862 extended to the south line of Section 27 in Township 18 N., Range 29 E., or a mile north of its edge in 1881.[128]

In 1861 the elevation of Walker Lake was about 4060 feet, for it stood 17 feet below the level of 1862 which in turn was 10 or 12 feet below the highest modern stand [129] of about 4088 feet. The flood of 1861-62 raised the lake 17 feet to 10 or 12 feet below its highest level, i. e. to about 4077 feet. The dead trees standing under four or five feet of water at the northern end of the lake in 1882,[130] when the level was about 4086 feet, may have grown during the eighteen-forties, fifties, and sixties and become drowned during the rise of the water in 1868. Pyramid Lake was very low in 1862, and dead trees standing in the water testified to previous still lower levels.[131] Pyramid Lake is supplied largely by the Truckee River, which normally discharges into this lake most of its water that has not been taken out for irrigation. The lake expanded and in 1867 stood at the level of 3876.82 feet.[132] It rose ten to fifteen feet in 1868 and continued rising in 1869, consequently reaching the level of 3895 to 3900 feet, its highest observed stand. During these two years it overflowed into Winnemucca Lake.

Winnemucca Lake in 1862 had been confined to the central part of its basin.[133] The stream channel that enters the lake extended beyond the shore at that time, and submerged dead cottonwood trees also showed that the lake had previously been much smaller, doubtless nearly or fully desiccated. Winnemucca Lake is largely supplied with water through a channel that extends from the Truckee River near its terminus in Pyramid Lake. The channel is probably a slough formed by overflow of Pyramid Lake into Winnemucca Lake.[134] Winnemucca Lake receives water when the Truckee is in flood and when Pyramid Lake is filled up to the fork of the river. The lake in 1867 was 80 feet lower than Pyramid Lake and consequently stood at an elevation of 3797 feet. It was then about thirty feet deep, or more than fifty feet below the level of 1882, when a depth of

[127] Russell (1885), 68.

[128] G. W. Likes, Fallon.

[129] Angel (1881), 406.

[130] Russell (1885), 70.

[131] *Ibid.*, 65.

[132] This is Clarence King's figure, 3890 feet (Russell, 1885, 64), corrected to the 1932 U. S. Coast and Geodetic Survey datum. According to information kindly given me by Mr. Harry C. Dukes, of Reno, the 1932 U. S. Coast and Geodetic Survey datum plus 4.18 feet equals the old Southern Pacific R. R. Co. datum, according to which the level of Pyramid Lake in 1867 was 3881 feet, not 3890.

[133] Russell (1885), 64.

[134] *Ibid.*, 43, 63.

87 feet was recorded.[135] From the great difference between the levels of the lakes in 1867 it may be concluded that for years previously most or all of the water of the Truckee River had discharged into Pyramid Lake. However, in 1867 the Truckee emptied into both lakes, and in 1868 and 1869 Pyramid Lake overflowed into Winnemucca Lake.

The seasons of 1863 and 1864 were extremely dry with disastrous effects for farmers and cattle raisers in California, and they were also dry in western Nevada.[136] The winter of 1866-67 was severe and snowy [137]; and the following winter was still wetter and snowier with bad floods in Nevada and California. One of the floods raised Walker Lake about seven feet.[137a] The winter of 1868-69 was likewise severe, causing great losses of cattle.[138]

According to information given to Mr. E. W. Kronquist of Schurz, Nevada, by old settlers, Walker Lake reached its highest recent stand in 1877. Since that particular year was exceptionally dry, this reference to it is surely due to a lapse of memory on the part of the old settlers. From what is known about the water supply in the region, it is most probable that the lake attained its highest level in 1868. This is supported by a statement in Angel's "History of Nevada" [139]—even though this cannot be fully correct—that except for the rises in 1862 and 1868 Walker Lake slowly receded during the sixties and seventies, chiefly because of diversion of water from the Walker River for irrigation. It being much easier to remember some point reached by the lake than to recall a year, its highest stand reported by the ranchers and determined by Kronquist to have been at an elevation of about 4088 feet is probably correct.

THE PERIOD 1871-1900

Since 1870 records have been kept of the meteorological conditions in the region. The stations have been divided here into two groups, one comprising those above and the other those below an altitude of about 5530 feet. One graph, which will be referred to as the "Truckee rainfall graph" (Plate I, j), is computed from the records of the stations Truckee (1870-1920), Boca (1870-1918), and Tamarack (1900-27), at 5818, 5535, and 8000 feet, respectively. Truckee and Boca lie east of the divide north of Lake Tahoe, and Tamarack south-southeast of Lake Tahoe. The average annual precipitations at the stations are 25.7, 20.6, and 47.3 inches. The bulk comes as snow during December to March. The average snowfall at Tamarack is 38 feet.

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[135] *Ibid.*, 56, 64, Pl. 9.

[136] Bancroft: California (1890), 2, 15; *Morning Appeal,* Carson, Sept. 13, 1889.

[137] Davis (1913), 178.

[137a] Angel (1881), 176, 406.

[138] Wren (1904), 167.

[139] Angel (1881), 406.

The other curve, which will be called the "Reno rainfall graph" (Plate I, i), has been compiled from the records of the following stations in western Nevada and adjacent regions of California: Reno (1880-), Carson City (1880-1906), Minden (1889-, incomplete), Smith (1909-), Markleeville (1910-27), and Shield's Ranch (1912-), standing at elevations of from 4532 to 5525 feet.[140] The mean precipitation at the stations ranges from 6.9 inches at Smith to 18.7 inches at Markleeville and averages 10.6 inches at all the stations. The greater part of the precipitation occurs during the months November to March. The rainfall of June to September is very light.

During most of the seventies and eighties the precipitation underwent large annual fluctuations. On the whole it was a little below the average during the first part of the seventies, dropped to a minimum in 1877, rose to a small maximum in 1880, and then gradually diminished till 1889, thus remaining subnormal for two decades. In 1890, however, the precipitation attained an extraordinary maximum, from which it decreased under fluctuations to a minimum in 1898.

Having attained in 1869 its highest level of 3895 to 3900 feet, Pyramid Lake began to fall, but in 1871 it was still nine feet higher than in 1867, or at a level of 3886 feet.[141] Winnemucca Lake, which in 1868 and 1869 received overflow from Pyramid Lake, rose 22 feet between 1867 and 1871, reaching a level of 3819 feet in the latter year.[141] The years 1870 and 1871 were unusually droughty in western Nevada,[142] and the summers of 1873 and 1875 were also dry.[143] On the other hand, the winter of 1873-74 was cold and snowy and extremely hard on livestock, and that of 1875-76 was rainy and snowy.[144] In the summer of 1876 a temporary gravel bar diverted the entire flow of the Truckee River into Winnemucca Lake. In fact, throughout the seventies most of the Truckee water may have gone into this lake, for it rose considerably, while Pyramid Lake subsided.[145]

The winter of 1879-80 was so cold and snowy that one-third of the cattle in Nevada perished.[146] Carson Sink was completely desiccated in October 1881,[147] not because of any unusual drought but probably on account of diversion of the spill water of the Carson River into Carson Lake, for this lake had in 1881 and 1882 an area of about 40 square miles and a depth of four feet throughout its central portion.[148] However, in September 1883 Carson Lake was very shallow; much of it presented the appearance of a swamp,[149] the year being unusually dry.[150] Pyramid Lake in 1882 was about 11 feet lower than in 1867—it stood at 3866 feet—and Winnemucca Lake was only 12 feet lower than the former lake, standing at 3854 feet.[151] The winter of 1883-84 was cold and snowy, entailing great losses of livestock.[152]

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[140] The records for Reno during the seventies indicate such an insignificant rainfall that they are surely not representative of conditions in the region. They are therefore omitted.

[141] Russell (1885), 64.

[142] *Morning Appeal,* Carson, Sept. 13, 1889.

[143] Wren (1904), 153.

[144] Peckham (1917-1920), 59, 67.

[145] Russell (1885), 65.

[146] Wren (1904), 166; Peckham (1917-1920), 73.

[147] Russell (1885), 68.

[148] *Ibid.,* 69; U. S. Bureau of Reclamation: Map No. 21444-A, 1925.

The summers of 1887, 1888, and 1889 were increasingly droughty, the last-mentioned season being the driest in the history of the state until 1931. In 1889 there was such a scarcity of water and pasturage that thousands of cattle died from thirst and starvation. On July 20 very little water was flowing from Lake Tahoe into the Truckee, although there was then no dam at the outlet.[153] In October the lake had receded to the level of 6222.1 feet, a stand not reached again till the fall of 1924.[154] Pyramid Lake in 1889 had receded to the level of 3861 feet, on account both of the drought and of the increasing withdrawal of water from the Truckee for irrigation purposes.[155] Winnemucca Lake probably continued rising till 1886 and then receded during the years 1887-89.

This extreme drought was abruptly broken by an enormous precipitation during the winter 1889-90, the severest ever experienced in Nevada. Since the shortage of water and pasturage had left the animals in a poor condition to face the cold and the blizzards, cattle and sheep perished by the thousands. About 95 per cent of the livestock in Nevada was lost.[156] During the following spring and summer Lake Tahoe rose 5½ feet, though there was no dam at the outlet, and Pyramid Lake rose 15 feet, attaining the elevation of 3876 feet, while Winnemucca Lake reached that of 3871 feet, its highest stand in recent time.[157] Deep snow lay all summer on Mt. Rose, fifteen miles south of Reno, and a small snowcap remained for several years. The winter of 1890-91 also brought much snow, blocking railroad trains for days in the Sierra. During the spring of 1891 the Truckee at Reno was a torrent for weeks and carried volumes of water well into the summer.[158] Pyramid Lake rose to 3879 feet, its highest stand since about 1875, and then resumed its recession; Winnemucca Lake, at 3867 feet, had already begun the decline that is still going on.[159] In 1893 there was plenty of water at Fallon, but in 1894 the South Fork of the Carson went dry early in the summer.[160]

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[149] Russell (1885), 45, 69.

[150] Wren (1904), 153.

[151] Russell (1885), 62, 64.

[152] Wren (1904), 168.

[153] Peckham (1917-1920), 104, *Morning Appeal,* Carson, Sept. 20, 21, 1889; *Fallon Standard,* Sept. 2, 1931.

[154] U. S. Weather Bureau: Climatic Summary . . . , Section 19—Nevada (1932), 26.

[155] Russell (1885), 42.

[156] Wren (1904), 168; Peckham (1917-1920), 104, 105; *Elko Independent,* July 29, 1931; *Fallon Standard,* Aug. 19, Sept. 2, 1931.

[157] U. S. Geol. Survey: Topographic Map, Wadsworth Quadrangle, Nevada (1: 125,000).

[158] *Fallon Standard,* Aug. 19, Sept. 2, 1931.

[159] U. S. Geol. Survey: Topographic Map, Granite Range Quadrangle, Nevada (1: 250,000).

[160] G. B. Williams, Fallon.

THE PERIOD AFTER 1900

Beginning in 1900 records have been made of the flow in the streams. The runoff curve presented (Plate I, g) is based on the discharge of the Truckee River at Tahoe (1901-), the West Fork of the Carson River at Woodfords (1902-20), the East Fork of the Carson River near Gardnerville (scattered seasons), the Carson River at Empire (1902-23) and near Fort Churchill (1911-), the West Walker River near Coleville (1902-09, 1914-), the East Walker River near Bridgeport (1921-), and the Walker River near Wabuska (1902-07, 1919-). The stream-flow records are compiled in the *Biennial Report of the State Engineer,* George W. Malone, Nevada, 1929-30. Most of the gauging stations lie below important diversions. The water is largely derived from the winter snows in the mountains, which for the most part rise to elevations of 8000 to 10,000 feet. The runoff is normally greatest during May, June, and July or during one or two of these months. It is normally at a minimum during September and October or in one of these months.

The rainfall and the runoff curves show notable agreement in respect to a general decrease from 1907 to the present, contemporary maxima and minima, and a similar trend in most of the years. They disagree, however, in the degree of the decline, owing largely to increasing diversion, and hence the adjusted runoff curve has been given the general trend shown by the rainfall graph. They also disagree in the prominence of the maxima and minima and in other features, owing to differences in the precipitation in the mountains and on the plains. The runoff was excessive in relation to the precipitation on the plains in 1904, 1906, and 1922 and relatively deficient in 1907, 1908, 1925, and 1930-32. The runoff and rainfall curves have opposite trends in 1901, 1917, and 1918.

The water supply, or precipitation and runoff combined, on the whole increased from the turn of the century till 1907, when it attained its latest great maximum, one comparable to that of 1890. Then it decreased, with notable secondary maxima, during the years 1911, 1914, 1922, and 1927, to the recent extreme minimum.

Lake Tahoe, the large and beautiful body of water in the Sierra Nevada that discharges through the Truckee, rose from 1900 to 1907 in fair harmony with the runoff of the region (see below, p. 37). Carson Lake in October 1903 stood at the level of 3911 feet[161] and was two feet deep, for the lowest point of the basin is at 3909 feet.[162] Pyramid Lake in 1904 stood at 3862 feet, or 17 feet below the level of 1891. The heavy precipitation of 1906-07 caused bad floods, as a consequence of which Carson Lake in the spring was nearly as high as in 1862.[163] Carson Sink, when surveyed for the U. S. Geological Survey's topographic quadrangle in 1908, was 12 by 15 miles in extent. Walker Lake in 1909 had an elevation of 4078 feet, for the datum plane of the Hawthorne quadrangle (surveyed in 1909), on which the altitude is given as 4083 feet, is five feet higher than the 1912 datum of the U. S. Coast and Geodetic Survey. Pyramid Lake rose during the rainy period after the turn of the century and in 1909 stood at 3869 feet. During the summer, when the Truckee River carried practically no water, Pyramid Lake overflowed into Winnemucca Lake, then at an elevation of 3846 feet.

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[161] U. S. Geol. Survey, Reclamation Service: *3rd Ann. Rept.,* 1903-1904, Plate 31.

[162] U. S. Bureau of Reclamation: Map No. 21444-A, 1925.

[163] L. Downs, Fallon.

The Truckee River was insufficient for irrigation needs in 1908, 1910, 1912, and 1913,[164] and Lake Tahoe was comparatively low in 1913. During January 1914 there were exceptional snowfalls in western Nevada. In Reno the January precipitation was the greatest in 24 years. Virginia City experienced the worst snowstorm in twenty-odd years. One storm deposited 16 feet of snow at Summit.[165] This heavy precipitation raised Lake Tahoe almost five feet and Pyramid Lake a foot and a half. Since 1915, when the Lahontan dam of the Carson River was completed, Carson Sink and Carson Lake have received only such water through the Carson as overflows the dam in the spring, a quantity that has usually been small. The Carson River was deficient in 1918, 1919, and 1920. During the same years Lake Tahoe subsided rapidly, and in July and August 1920 the Truckee River was so low that loss of crops was averted only by pumping water from Lake Tahoe into the river.[166] The Walker River failed in August 1921. About 1919 Walker Lake began to fall at a rate of three feet a year and was still subsiding in 1936.

The drought of 1918-21 was broken the following winter. In February 1922 the snowfall at Reno and other points in western Nevada exceeded all previous records for the month. The runoff that year was unusually large, Lake Tahoe rose, and Carson Lake was relatively high, being two to three feet deep. However, with the exception of March, every month of the rainfall year October 1923-September 1924 had deficient precipitation, and as a result the snow cover in the mountains was extremely light and the water supply insufficient for the needs of irrigation. Lake Tahoe dropped about three feet, and in August and September water had to be pumped from the lake into the Truckee. In October the lake for the first time fell below its rim established at 6222 feet in 1904. The Carson River was lower than ever before. Carson Lake shrank to an area of three by four miles.[167] Except for 1889 the growing season of 1924 was the driest on record in western Nevada up to that date.[168] During the year 1924-25 the precipitation was comparatively heavy on the plains, but small in the mountains, and the runoff deficient. In 1926 a thin snow cover in the mountains, its partial loss by early melting, and a subnormal rainfall during the growing season together caused a pronounced shortage of water and loss of crops in many localities. The Truckee and Carson rivers, among others, were extremely low. Heavy rains and quickly melting snows during the last week of March 1928 swelled the Truckee and Carson rivers and were of great benefit to crops and pastures, but the rains melted the little snow that was stored in the mountains, so that a shortage of water made itself felt along the Carson River as early as July 6.[169] Deficient precipitation during the winter months and drought beginning June 19, 1929, caused an acute lack of water for irrigation in the latter part of August with accompanying losses to ranchers.[170] Carson Lake became dry in July and remained so in 1930 and 1931.[171] In the fall of 1929 Lake Tahoe for the second time dropped below its rim. Subnormal snow and rain from December 1930 to July 1931 combined with high summer temperatures caused an exceptionally severe drought, with disastrous effects upon agriculture and stock raising. The year ranks with 1889 as the driest in the history of the state up to that date. Water was generally sufficient only for one or two irrigations. Some springs and wells dried for the first time since they had been used by ranchers.[172] Since about 1917 Carson Sink has received no water from the Humboldt River and little water from the Carson.[173] In 1930 the lake consisted of fairly large sheets of water in various parts of the extremely flat basin,[174] but by the autumn of 1931 it became completely dry. A yellow-white silt floor extended as far as the eye could reach. No salt crust was seen, though during the desiccation in 1881 there had been salt crusts in places.[175] Heavy snowfall in the mountains during the months November to February 1931-32, and precipitation near normal during the growing season provided ample water for irrigation in 1932, except in the Truckee valley. Here the Truckee River failed because a large part of the water derived from the snow that had fallen in the watershed of Lake Tahoe was required to fill the lake to the level of the dam at 6222 feet, after the lake in December 1931 had reached the lowest level (6220.8) recorded up to that time. In 1933 a rainfall that amounted to only 60 per cent of the average and a runoff that was subnormal resulted in a summer and autumn drought. In 1934 the precipitation at the meteorological stations was above the average, but the snowfall in the mountains was so exceedingly light that an acute shortage of water developed. On December 26, 1934, Lake

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[164] U. S. Bureau of Reclamation: Reports . . . Kittitas Division (1925), 193.

[165] *Carson Appeal,* Jan. 7, 20, 28, Feb. 3, 1914.

[166] Nevada: Biennial Report (1919-1920), 12, 14.

[167] U. S. Bureau of Reclamation: Map No. 21444-A, 1925.

[168] U. S. Weather Bureau: Climatological Data, Nevada (1924), 57; Nevada: Biennial Report (1923-1924), 6, 7.

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[169] Nevada: Biennial Report (1927-1928), 47.

[170] U. S. Weather Bureau: Climatological Data, Nevada (1929), 53.

[171] Mr. York, Fallon.

[172] U. S. Weather Bureau: Climatological Data, Nevada (1931), 79; *Fallon Eagle,* Sept. 5, 1931.

[173] According to Mr. Webb, a cowherder, probably of Fallon.

[174] *Fallon Eagle,* Aug. 29, 1931.

[175] Russell (1885), 68.

Tahoe stood at 6220.75 feet, the lowest level since records have been kept. Carson Sink and Carson Lake contained small ponds of water throughout the summers of 1932 and 1933, but most of these dried in 1934.[176]

In 1935, 1936, and 1937 the water supply was plentiful, and Carson Lake and the eastern part of Carson Sink contained a considerable amount of water. In 1936 the Lahontan Reservoir spilled over for the first time since 1926.[176a]

Certain figures on levels and some added data regarding the lakes may be given (see Plate I, f). Since 1904 Lake Tahoe has had an established elevation at 6223 feet (old datum) above mean sea level, and the zero of the gauge has been at 6220 feet (old datum).[177] This level of the lake was officially established by a stipulated decree of June 1915 by the United States Federal Court for the Northern District of California, in the case of United States vs. the Truckee River General Electric Co. However, a general adjustment by the U. S. Coast and Geodetic Survey in 1929 showed these elevations to be 0.99 feet too high (i. e. that zero of the gauge stands 6219.01 feet above mean sea level, and the rim at 6222.01 feet). The 1929 datum was first used in the *U. S. Geological Survey Water-Supply Paper 790*, 1935. In the present paper all elevations are given in relation to the 1929 datum, as are also the levels shown by the curve, Plate I, f.

Data on the maximum elevations of the lake for five years between 1887 and 1900 and data on the maximum and minimum elevations since 1900 are published in *U. S. Geological Survey Water-Supply Paper 270* and later issues of this series, and all the data before 1930 are compiled in the *Climatic Summary of the United States, Section 19, Nevada*, 1932, p. 26. The accompanying graph (Plate I, f) shows the means of the maxmum and minimum stands for each water year. From the occurrence of a tree stump with 100 annual rings two feet below the level of the rim and of stumps with 150 rings at the rim of the lake, Harding [178] concludes that Lake Tahoe stood at least two feet below its modern rim from about 1760 to 1860. However, since all stumps occurred at Tallac, at the south end of the lake 16 miles from the outlet, it is possible that their submergence has been due to a warping of the lake basin producing a relative rise of the outlet. Wide growth rings formed about 1810 in trees north of Lake Tahoe [179] and from 1801-1821 in trees at Susanville suggest heavy rainfall and make it almost certain that Lake Tahoe then stood at and above its outlet and would have submerged and killed the tree at Tallac, if it had grown below the outlet level.

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[176] D. S. Stuver, formerly of Fallon.

[176a] Mr. A. B. Purton of Salt Lake City, Mr. H. D. McGlashan of San Francisco, and Messrs. W. H. Wallace and Claude H. Smith of Fallon, Nevada, have kindly supplied as yet unpublished data on runoff and lake levels.

[177] Surface Water Supply of the United States, 1909, Part 10. *U. S. Geol. Survey Water-Supply Paper 270* (1911), 108.

[178] Harding (1935), 88, 89.

[179] Hardman and Reil (1936), 27, 29.

The elevations of Pyramid Lake have been measured since 1867 by Clarence King, I. C. Russell,[180] the U. S. Geological Survey, the Southern Pacific R. R. Co., L. F. Canterbury, J C. Jones, and Harry C. Dukes, and the current levels are being published by the U. S. Geological Survey.[181] All the data have been compiled and kindly submitted by Mr. Dukes. The elevations are given with reference to the 1932 datum of the U. S. Coast and Geodetic Survey, which is 4.18 feet less than the old Southern Pacific R. R. Co. datum. Of the several yearly measurements beginning 1927 only the high and the low are given. In recent years only a little waste water has reached Pyramid and Winnemucca lakes, for the precipitation has been light, and part of the Truckee River water is diverted at Derby into the Truckee Canal for the Lahontan Reservoir on the Carson River, and the part that is sent down the river channel is largely taken out for irrigation at Pyramid Lake Indian Reservation. In August 1937 Pyramid Lake was about 80 feet below its highest recent stand in 1869. It was 313 feet deep, the lowest point of the basin standing at an elevation of 3505 feet.[182]

WATER SURFACE ELEVATIONS OF PYRAMID LAKE (IN FEET)

1844		3860 (about)	1922	Aug. 26	3856.1	1933	Jan. 28	3829.0
1867		3876.8	1924	Mar. 22	3853.9	"	May 19	3827.5
1869		3897 (about)	1926	May 11	3848.4	"	June 26	3827.9
1871		3885.8	1927	Jan. 22	3845.7	"	Dec. 22	3825.7
1882		3865.8	"	June 18	3846.6	1934	Mar. 15	3825.5
1889		3860.8	"	Oct. 10	3844.7	"	June 17	3825.0
1890		3877.8	1928	Mar. 18	3844.2	"	Aug. 18	3824.1
"		3875.8	"	Apr. 27	3845.1	"	Dec. 20	3822.6
1891		3878.8	"	Oct. 18	3843.3	1935	Apr. 26	3821.7
1904		3861.8	1929	May 18	3841.5	"	June 9	3822.6
1909	Apr. 16	3869.1	"	Sept. 20	3839.8	"	Aug. 20	3821.6
1911	July	3869.6	1930	Mar. 27	3838.6	"	Dec. 23	3819.9
"	Oct.	3867.8	"	June 12	3837.9	1936	Mar. 19	3819.5
1912	June 14	3866.8	1931	May 22	3835.5	"	June 21	3820.4
1913	July 7	3864.8	"	Oct. 20	3831.5	"	Aug. 18	3819.7
1914	Feb. 28	3864.1	1932	Jan. 23	3831.6	"	Dec. 19	3817.8
"	July 20	3866.3	"	Apr. 15	3831.3	1937	Feb. 17	3816.8
1915		3861.5	"	June 21	3831.8	"	May 15	3818.7
1917		3861.4	"	Dec. 24	3829.3	"	Aug. 27	3817.8

The elevations of Winnemucca Lake have been measured by Clarence King, I. C. Russell,[183] and the U. S. Geological Survey, and also by

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[180] Russell (1885), 64.

[181] Surface Water Supply of the United States, 1935, Part 10. *U. S. Geol. Survey Water-Supply Paper 790* (1937), 80.

[182] Russell (1885), 56, Pl. 9.

[183] *Ibid.*, 64.

L. F. Canterbury whose measurements have been kindly put at my disposal by Mr. D. S. Stuver. In 1867 Winnemucca Lake was 80 feet lower than Pyramid Lake, in 1890 five feet lower and in 1926 37 feet lower. It rose 74 feet from 1867 to 1890, then dropped 60 feet to 1926. Mr. W. H. Wallace of the Newlands Reclamation Project informed me in August 1937 that Winnemucca Lake had not received any water from the Truckee River since the spring of 1928, and that the lake has lately subsided at a rate of about four feet a year. On April 6, 1936, the lake was 10 feet deep, on August 1, 1937, four feet, and it will probably be completely dry in the autumn of 1938.

Water Surface Elevations of Winnemucca Lake (in Feet)

1867	3796.8	1891	3866.8
1871	3818.8	1909	3845.8
1882	3853.8	1922	3821.6
1890	3870.8	1926	3811.0

Because the Truckee River frequently has not discharged the same relative quantities of water into Pyramid and Winnemucca lakes but at times has sent either all or the bulk of its water to only one of them, the fluctuations of each lake do not record the water variations in the common basin. Therefore, the mean level of the two lakes is given in Plate I, f, the area of Pyramid Lake being taken as two and one half times that of Winnemucca Lake.

Walker Lake, which probably attained its highest recent stand, about 4088 feet, in 1868, has in late years taken the levels given in the table below, according to readings made by the U. S. Coast and Geodetic Survey, the U. S. Geological Survey, E. W. Kronquist, and the U. S. Navy Department. Of the numerous measurements by the Navy Department since August 1928, published in *U. S. Geological Survey Water-Supply Papers 705, 720, 735, 750, 765,* and *790,* only the highest and lowest levels of each year are given. All the figures refer to the 1912 datum of the U. S. C. & G. S., which, as we have seen, is five feet lower than the datum plane of the Hawthorne quadrangle. According to Mr. Kronquist the lake was 185 feet deep in 1929(?), when its surface stood at an elevation of about 4047 feet; this shows that the level of the bottom of the lake is about 3862 feet. From the culmination in 1868 the surface dropped slowly until about 1919, after which it has fallen (at an average rate of three feet a year) because only a little water from the Walker River has reached the lake. The 1936 level stood 65 feet below the culmination in 1868, and the lake was about 161 feet deep.

Water Surface Elevations of Walker Lake (in Feet)

1861			4060	(about)
1862			4077	"
1868	(?)		4088	"
1882			4086	"
1908	Sept.	27	4078.0	
1909			4078.0	
1919	July		4074.0	
1923	July		4066.5	
1924	June		4064.3	
1925	April		4061.7	
1927	Mar.	11	4054.7	
1928	Mar.	13	4051.8	
"	Dec.	11	4048.2	
1929	Feb.	21	4048.2	
"	Dec.	31	4045.0	
1930	Jan.	9	4044.9	
"	Dec.	1	4041.3	
1931	Jan.	30	4041.3	
"	Dec.	31	4037.8	
1932	Sept.	24	4036.0	
1933	Jan.	3	4034.6	
"	Aug.	11	4033.4	
1934	Jan.	24	4031.3	
Water year 1935,		high	4028.6	
		low	4026.2	
Water year 1936,		high	4025.7	
		low	4023.0	

CHAPTER IV

THE HUMBOLDT REGION, NORTHERN NEVADA

THE PERIOD BEFORE 1871

In regard to the moisture conditions in the Humboldt region only historical and traditional data are available for the period before precipitation measurements were begun in 1870. The rainfall at Sacramento and San Francisco and the tree growth at Susanville and Lakeview cannot be taken even as approximate indicators because, for the period since 1871, they differ too much from the recorded rainfall of the Humboldt region.

In 1841 the Humboldt River was so low that it could be crossed dry-shod in several places.[184] Also in August 1846 it was locally almost dry. At the same time Humboldt Lake consisted of "some pools of standing water . . . covered with a yellowish slime, and emitting a most disagreeable fetor." The water was too alkaline for either man or beast to drink.[185] The basin of Humboldt Lake owes its existence to a large gravel barrier built across the Humboldt valley in the pluvial Lake Lahontan. Overflow of the ponded water has cut through the embankment at its lowest point. The outlet river terminates in Carson Sink.[186] The winter of 1848-49 brought plenty of snow, and the following spring was cool and wet, producing unusually luxuriant grass in the region of Winnemucca.[187] In 1850 the Humboldt River was extraordinarily high. It overflowed the old trail, turning it into a quagmire, and drove the emigrant trains for California to the barren uplands.[188] Even in June the Humboldt Range was covered with snow. Humboldt Lake formed a large sheet of water extending two to three miles farther north and west than it did in 1849. The water was alkaline but drinkable.[189] On July 29, 1859, Humboldt Lake was "a fine sheet of clear water, perhaps fifteen miles in length and forty in circumference." It overflowed by a small river to Carson Sink.[190] About 1860 Horace Greeley built a dam across the gap in the embankment, by which the water was ponded higher and the area of the lake was considerably increased. The lake then extended to within two miles southwest of Lovelock. Below the dam Greeley erected a quartz mill for local gold ore.[191]

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[184] Bancroft: Nevada (1890), 53.

[185] Bryant (1848), 195, 213.

[186] Russell (1885), 66, 105.

[187] Hulbert (1931), 216.

[188] Bancroft: California (1888), 159; Sawyer (1926), 72, 73, 76, 80.

[189] Sawyer (1926), 86-89.

[190] Greeley (1860), 273.

[191] John T. Reid, Lovelock.

The Period 1871-1903

Since 1870 meteorological records have been kept in the region. The precipitation curve here reproduced (Plate II, s) is based on the data of the stations Arthur (1911-), Crane's Ranch (1889-1904), Elko (1871), Eureka (1903-18, 1923-30), Halleck (1871-1915), Hylton (1911-), North Fork (1911-), and Wells (1871-1914) on the upper Humboldt and its tributaries. The stations range in elevation from 5077 to 7081 feet. The mean precipitation of all the stations, calculated in terms of rainfall years, is 10.8 inches. The rainfall is lightest, 7.9 inches, at Halleck (alt. 5232 ft.) and heaviest, 14.9 inches, at Arthur (alt. 6500 ft.). The bulk of the precipitation occurs during the months December-March with a secondary spring maximum in May. In July, August, and September the rainfall is exceedingly light. The winter rains or snows are brought by the general cyclonic storms, the moisture coming largely from the Pacific Ocean. The spring and summer rains are usually of local convectional origin.[192]

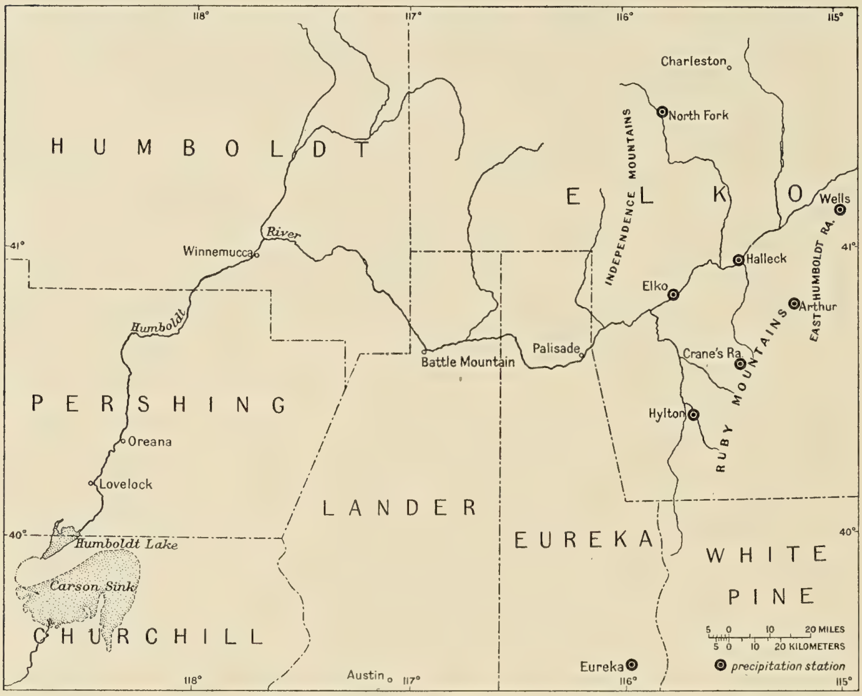

Fig. 5—Map of the Humboldt region, Nevada. Scale, 1: 3,000,000. The rainfall curve for the region (Pl. II, s) is based on records for the precipitation stations indicated.

The measured rainfall in the region undergoes relatively small annual fluctuations, and the differences between the maxima and the minima are moderate. The precipitation at the stations Elko, Halleck, and Wells had a low maximum in 1872, a minimum in 1875, and another low maximum in 1876 and 1877. Whether or not this rainfall on the plains was representative of the water supply, which is largely determined by the snowfall in the mountains, is not known, but the rainfall minimum in 1878 and 1879 was typical. On the other hand, the precipitation during most of the eighties was not characteristic, as seen from the following data. After the marked minimum in 1888 and 1889 the rainfall abruptly rose to a high maximum in 1890 and remained excessive till 1908.

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[192] Ward (1925), 196.

The water supply of the Humboldt River at Lovelock has been briefly recorded since 1879 by Mr. W. C. Pitt of Lovelock.[193] In 1879 the Humboldt was extremely low, even less water reaching the Lovelock region during the growing season than in 1929. During 1880 and 1881 the water supply amounted to the average. In 1882 the water was high, breaking Farmers dam. About 1882 the Humboldt River usually terminated in Humboldt Lake during the dry season, but during the winter months it continued from the lake into Carson Sink. In July 1882 Humboldt Lake covered an area of about 20 square miles, did not overflow, and although somewhat alkaline was inhabited by both fish and mollusks and was sufficiently pure for human use. It had a nearly uniform depth of 12 feet in the central parts.[194] The runoff increased during the two following years. In 1883 Farmers dam, Sigman dam, and Marzen dam all gave way. In 1884 the water filled the entire river channel and overflowed the banks. Marzen dam, which had been replaced, was destroyed, and so was Southwest dam, which also was new. During the summers 1885, 1886, and 1887 the Humboldt brought a good supply of water, " plenty and to spare." In 1888 the river was low throughout the growing season, and the supply insufficient. The following year the river brought only an insignificant amount of water in April and later went entirely dry. The river bed was also quite dry much farther up, near Halleck.[195] Humboldt Lake was dry, so that a surveying party had to sink wells for water.[196]

The extraordinarily snowy and severe winter of 1889-90 was followed by floods, which washed away all the dams near Lovelock. During the years 1892-95 the Humboldt had plenty of water. In 1896 water was short at Lovelock, according to Pitt, while near Oreana, some fifteen miles upstream, the discharge was about one and a half times as great as in 1895.[197] In 1897 the water supply was ample at Lovelock and Oreana and also at Palisade, between Battle Mountain and Elko.[197] During 1892-97 Humboldt Lake was filled to the gates and overflowed to Carson Sink.[198] In 1898 the Humboldt River carried sufficient water at Lovelock during the early and the late parts of the growing season but not during the middle part. At Oreana and Palisade the discharge was small. During 1899 the water supply was ample at Lovelock and plentiful at Oreana and Palisade. In 1900 the discharge was insufficient at Lovelock in April and was also small at Oreana and Palisade. During the following year there was plenty of water at Lovelock, a fair supply at Oreana, and a small amount at Palisade. In 1902 there was some water in the spring at Lovelock, little water at Oreana, and a fair amount at Palisade. In 1903 the water supply was barely sufficient—much below the average.

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[193] Pitt (1929).

[194] Russell (1885), 40, 66, 67, 106, Pl. 18.

[195] *Elko Independent,* July 29, 1931.

[196] John T. Reid, Lovelock.

[197] Nevada: Biennial Report (1929-1930), 205, 206.

The Period After 1903

Beginning in 1903 there are records of the discharge of the Humboldt River at Palisade, which have been compiled by A. V. Tallman and H. P. Boardman.[199] The Humboldt has its largest volume at Palisade. Practically half of the total diversion from the Humboldt is made above this point.[200] Increase of the amount of the water yearly diverted since 1903 is undoubtedly one of the causes of the general drop of the runoff graph towards the present. However, a change of the runoff curve to the same trend as that shown by the rainfall curve would result in an overcorrection for diversion, judging from the comparative reports of the droughts. Therefore the runoff graph, somewhat arbitrarily, has been given a trend intermediate between those of the rainfall and the measured runoff. With this correction for trend the runoff curve agrees well with other data (Plate II, r).

In February and March the flow of the Humboldt is largely supplied from the benchlands between 5500 and 6500 feet (the river at Palisade has an elevation of about 4800 feet). From April to July inclusive the water is derived almost wholly from the higher levels of the Independence (Charleston) Mountains on the north and the Ruby Mountains on the south.[201] The former range, which attains elevations of some 10,000 feet, is relatively gentle, and its slopes that feed the Humboldt face the sun; here the melting of snow and the runoff are greatest in April. The steep-ridged Ruby Mountains reach 12,800 feet in height; their northwest slopes, which feed the Humboldt, are protected from the sun, and the stream flow reaches its climax in June.[202] As a consequence the flow of the Humboldt at Palisade is at its peak throughout April, May, and June; and the normal distribution of the flow at Palisade from March to

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[198] L. H. Taylor, Reno.

[199] Nevada . . . : Humboldt River (1932), 71-73, 93.

[200] Church (1932), 92.

[201] *Ibid.*, 87.

[202] *Ibid.*, 88.

July inclusive is as follows: March, 16 per cent; April, 22; May, 25; June, 27; July, 10 per cent.[203] While the bulk of this water is derived from snow, a considerable amount comes from rains, there being, as mentioned, a secondary precipitation maximum during the month of May.

The stream-flow graph (Plate II, r) in contrast with the rainfall curve, presents sudden and great fluctuations. The runoff was excessive in relation to the measured rainfall in 1907, 1909, 1914, and 1921 and relatively deficient in 1905, 1908, 1913, 1915, 1918, 1920, 1923, 1926, and 1928-31. The smoothed curves show essentially the same trends. Tallman [204] finds " very little relationship " between the runoff at Palisade and the *average* of the annual precipitation of approximately the same stations as those employed by the present writer. The discrepancies may be due to various causes. Tallman attributes them largely to diversions on the tributary streams between their sources and Palisade. Church [205] refers the tendency of the river to " flash " up and down to the character of the stream bed and to unauthorized diversions out of proportion to the water available. The stream bed is silty and porous, mostly of low gradient, and has numerous tight dams which cause seepage and diversion. The loss of water en route is proportional to the height of the stream. Since the porous soils have a great storage capacity for water, the flow during one year has a fundamental influence on the succeeding year's runoff. During a dry year the moisture of the stream bed gradually disappears and must be replaced from the new year's water supply. During a year of excessive runoff large quantities of water are stored which greatly increase the flow of the following year.[206] Another important cause of the discrepancies between the two curves may be differences in the relative precipitation at the comparatively low levels of the rainfall stations and in the high mountains that serve as the main catchment areas of the precipitation represented by the stream flow.

The precipitation on the plains and the runoff were ample in 1904. The latter was somewhat deficient during the following year and then increased in two years to attain its greatest recent climax. It dropped suddenly, however, and as early as 1908 was a little short for the irrigation needs at Lovelock, although the plains rainfall remained high. Although the rainfall was small in 1909, the Humboldt River carried enough water. In March 1910 the greatest flood on record came down the Humboldt, causing damage along its entire length. It changed the channel at various points, destroyed nearly all the dams, carried away bridges, and inundated wide tracts of cultivated land.[207] The flood deposited a layer of silt a foot to a foot and a half thick in Humboldt Lake near the mouth of the river.[208] The stream-flow curve fails to record this flood because the runoff was not measured anywhere that spring.

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[203] *Ibid.*, 89.

[204] Nevada . . . : Humboldt River (1932), 41.

[205] Church (1932), 94, 102.

[206] *Ibid.*, 95, 97, 98.

[207] Nevada: Biennial Report (1909-1910), 20.

In 1911 and 1912 the precipitation and the stream flow were of the average amount, but in 1913 the former was well above, the latter somewhat below the average. The river was unusually high in 1914; during the following year it became exceedingly low, bringing insufficient water. The water supply was barely adequate in 1916. During the winter of 1916-17, which started early and ended late, exceptional quantities of snow accumulated in the Ruby Mountains. Together with heavy and frequent rains in the spring and early summer this snow produced a surplus of water and delayed the start of the growing season.[209] During the three years 1918-20 the rainfall was subnormal and the runoff exceptionally small. Near Lovelock, in fact, there was little or no flow in the Humboldt.[210] During the next year the water supply changed to the other extreme and was more than twice the normal amount. In that year and the following there was considerable water in Humboldt Lake and some overflow to Carson Sink.[211] The precipitation and runoff then decreased. During the rainfall year 1923-24 the snow cover in the mountains was extremely light and the precipitation at the stations was the smallest on record. As a consequence there was a severe drought during the growing season. Humboldt Lake dried. In 1925 the rainfall was comparatively heavy and the runoff fair. Humboldt Lake again contained some water. Because of light snowfall in the mountains and depletion of the snow cover by exceptional melting during the early spring the Humboldt River in 1926 was lower than it had been since 1889.[212] Humboldt Lake dried up and did so again in the summers of 1927-34.[213] In 1931 its dry floor, which consists of clay and silt, was firm and hard. The lake bed is now cut through by a drainage canal, and, even if the Humboldt were to bring a considerable supply of water to the lake, this canal would permit but a small part of it to remain in the basin; the rest would go through to Carson Sink.[213] From the latter part of 1926 till the end of 1931 the Humboldt carried no water past Lovelock.[214] At Palisade the runoff decreased steadily from 1927 to 1931, and in 1928 the Humboldt River carried little water at Battle Mountain after the end of April.[215] During the growing season of 1929 there was somewhat more water available at Lovelock than in 1879, but the fall was to that date the driest in the history of the region. In 1930 an insignificant runoff was partly balanced by unusually beneficial rains during the month of May.[216] The long and disastrous drought attained a first culmination in 1931, when the lightest snowfall so far recorded in the mountains and an intense summer heat reduced the runoff at Palisade to 12 per cent of its normal amount.[217] The months November 1931 to February 1932 were exceptionally cold and snowy and caused considerable loss of cattle and sheep; but the accumulated deep snow provided ample water for irrigation during the following season. However, this did not mark the definite turn to a time of heavier precipitation, for in 1933 the water supply was again deficient,[218] and 1934 was the driest year ever experienced in the region, the runoff at Palisade being only 9 per cent of the normal.[219] Because the ground and the river channels were dry after the drought year 1934, the exceptional rainfall during March, April, and May 1935 and the average precipitation for the whole rainfall year produced at Palisade a runoff of only 57 per cent of the normal.

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[208] John T. Reid, Lovelock.

[209] Nevada: Biennial Report (1917-1918), 7.

[210] *Ibid.* (1929-1930), 207.

[211] L. H. Taylor, Reno.

[212] Nevada: Biennial Report (1925-1926), 8.

[213] John T. Reid, Lovelock.

[214] Nevada: Biennial Report (1929-1930), 207.

[215] *Ibid.* (1927-1928), 46.

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[216] *Ibid.* (1929-1930), 41.

[217] Nevada: Report (1931-1932), 36.

[218] Nevada: Biennial Report (1932-1934), 41.

[219] *Ibid.* (1932-1934), 42, 55; (1934-1936), 51, 73.

CHAPTER V

THE GREAT SALT LAKE REGION, UTAH

THE PERIOD BEFORE 1871

Until 1870, when rainfall measurements were begun in Utah, we are dependent on history and tradition for information about the precipitation. The Sacramento rainfall does not correspond sufficiently well with that of the region to furnish a reliable clue to the trend of the latter before 1870. The tree-growth curves for Susanville and Lakeview would also be doubtful indicators, even though the smoothed graphs fairly well match the smoothed local rainfall graph after 1870.

During the winter of 1829-30 snow is reported to have fallen in the Great Salt Lake region for seventy days in succession. It buried the vegetation under such a deep blanket that the entire stock of bison in the region died from starvation.[220] The precipitation must have been subnormal for a long time previous to 1845, for Great Salt Lake is estimated by Harding [221] to have stood that year at an elevation of about 4201 feet, judging from Frémont's description of riding to Antelope Island through water that nowhere came above the saddle girths. In 1848 Great Salt Lake was so low that a bar connected Antelope Island with the mainland, a bar not again exposed till 1900, when the lake stood at an elevation of 4199 feet.[222] Drought, frost, and, above all, grasshoppers caused famine among the Mormons in the fall of 1848, the year after their arrival in the region.[223]

The levels of Great Salt Lake are known since 1851 from traditional data and since 1875 from gauge measurements. All the data for the period 1851-1923 have been compiled by Woolley.[224] Records after 1923 are to be found in the *U. S. Geological Survey Water-Supply Papers,* Surface Water Supply of the United States, Part 10. The accompanying curve (Plate I, f) gives the mean levels, i. e. the averages of the annual maxima and minima for years ending September 30.

Because of its large size Great Salt Lake is scarcely influenced by the excessive or deficient rainfall or stream flow of a single year. It responds to the cumulative effect of the runoff of two or more years. A rising lake level corresponds to a period of excessive stream flow, and the rise

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[220] Bancroft: Nevada (1890), 3, 4.

[221] Harding (1935).

[222] Murdoch (1901).

[223] Whitney, Vol. 1 (1892), 397.

[224] Woolley (1924), Pl. 2.

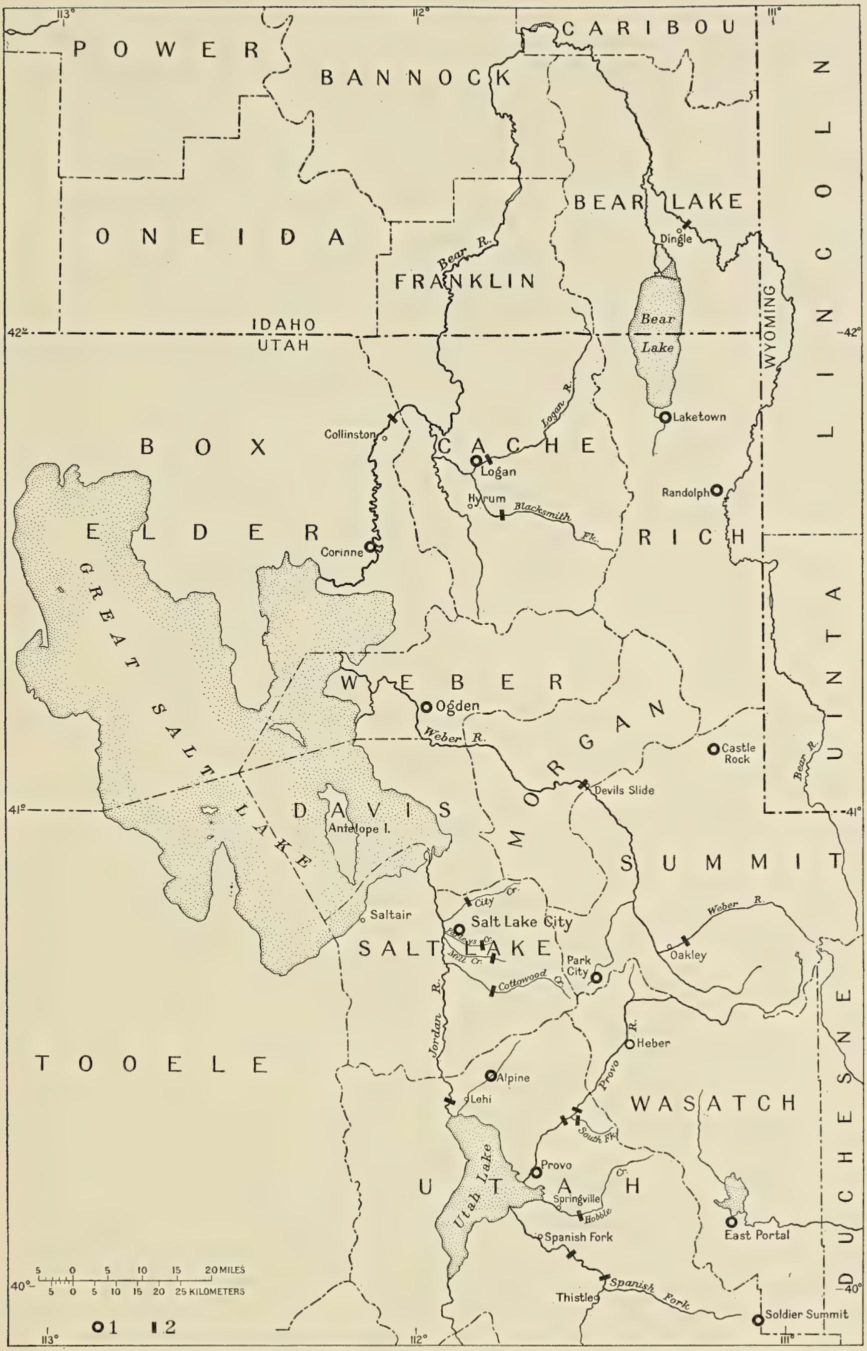

FIG. 6—Map of the Great Salt Lake Region, Utah and Idaho. Scale, 1: 1,795,000. The rainfall (Pl. II, w) and runoff curves (Pl. II, t, u, v) for this region are based on the records for the precipitation stations shown by symbol 1 and the gauging stations shown by symbol 2, respectively.

of the lake culminates about two years after the rainfall attains its maximum. The lake not only records but emphasizes the major fluctuations in precipitation and runoff. The withdrawal of water from the tributary streams for irrigation ever since the settling of the region in 1847 has naturally kept the lake at lower levels than it would otherwise have taken. It has reduced the highest stages and above all emphasized the minima. For instance, the constant increase of the withdrawal made the lake level of 4200 feet in 1931 represent a greater actual runoff in the tributary streams than did the same level in 1908.

During the eighteen-fifties the levels of Great Salt Lake fluctuated within the same limits and in much the same manner as during the nineteen-twenties. The water was mostly somewhat below its average level since 1851, which is about 4203 feet. Little or no water being diverted for irrigation during the forties and fifties, the rainfall then must have been actually less than during the period from 1910 to 1930. The steady rise of the lake in the years 1851-55 indicates increase in the precipitation for some years beginning about 1849. This was interrupted by a severe drought in 1854 and 1855, which, together with crickets, destroyed the crops.[225] In 1855 grasshoppers devoured every green thing in many parts of Utah. These two years of crop failures were followed by the terrible snowy winter of 1855-56, during which cattle died by the thousands from cold and starvation. As a consequence famine visited Utah during the first half of 1856.

Because of the drought in 1854 and 1855 Great Salt Lake began to fall in 1856 and continued to recede until the latter part of 1861. From this we may conclude that the precipitation was probably on the whole below normal until about 1859. In 1860 there were heavy floods in various parts of Utah.[226] The rapid rise of the lake level between the beginning of 1862 and the summer of 1869 shows that the sixties must have had a generous precipitation which probably reached its climax in 1867 or 1868. In December 1867 the rains in southern Utah were, in fact, too abundant, causing the rivers to swell far beyond their usual volume. The Virgin and Santa Clara rivers, in the southwestern corner of the state, almost completely swept away several small towns.[227] In the late sixties summer showers were frequent in Utah.[228] In 1867 Great Salt Lake submerged an old storm line at an elevation of 4207 feet, which in 1850 formed the lower limit of sagebrush growth.[229] Believing that a long time would be required after a submergence to leach the salt from the soil so that sagebrush could grow, Gilbert [230] concluded that the lake had probably not been above the storm line for perhaps several hundred years. Another old storm line at 4213 feet was not quite reached during the culmination of the lake in 1873 at an elevation of 4211.5 feet.

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[225] Tullidge (1886), 113; Whitney, Vol. 1 (1892), 547.

[226] Bancroft: Utah (1889), 723.

[227] Whitney, Vol. 2 (1893), 178.

[228] Bowles (1869), 225.

[229] Stansbury (1852); Harding (1935), 87.

[230] Gilbert (1878), 65.

THE PERIOD 1871-1899

Meteorological records have been taken in the region since 1870. The precipitation (Plate II, w) has been calculated from the data of the stations Logan (1893-), Corinne (1871-), Ogden (1871-), Salt Lake City, (1875-), Provo (1891-), and Alpine (1904-) at altitudes of from 4240 to 4900 feet, and Laketown (1901-), Randolph (1905-27), Castle Rock (1905-27), Park City (1891-, incomplete), Heber (1894-), East Portal (1913-21), and Soldier Summit (1894-1907, 1925-) ranging in elevation from 5559 to 7606 feet. The first group of stations has a mean annual (October to September) precipitation of 15 inches. Of all the stations, Randolph, at an elevation of 6442 feet, has the smallest precipitation, 10.2 inches; and Park City, elevation 7000 feet, has the largest, or 21.8 inches, the bulk of it being snow. In general, precipitation increases with altitude; and probably some 80 per cent of the water in the streams comes from areas above 7000 feet.[231] Since precipitation at these altitudes shows hardly any relationship to that in the valleys and on the plains where most of the rainfall stations are located,[231] the measured precipitation is no sure indicator of the runoff. About three-fourths of the annual precipitation in the region occurs from November to May, and only about 13 per cent in June, July, and August. The precipitation during the period October-June is brought about by the cyclonic storms that move in a curve across the continent from the northwestern to the northeastern states. During July, August, and September the rainfall results from local storms caused by the ascent of warm air on the mountain sides.

The maintenance of the unusually high level of Great Salt Lake from 1869 to 1877, with a highest stand of 4211.3 feet in July 1877, indicates a large runoff till about 1876. After a culmination that year the precipitation decreased to a marked minimum in 1879-83, and the lake level fell correspondingly till the end of 1883. Then the rainfall abruptly increased to a maximum in 1884, and the lake rose a few feet till 1886. The precipitation thereafter diminished to another decided minimum in 1887-89, and the lake followed about two years behind. Again the rainfall had a sudden climax in 1890, but this had no other effect on Great Salt Lake than to halt its decline for two years. During the remainder of the nineties the rainfall was on the whole a little subnormal, and the lake continued a slow subsidence except for halts in 1894 and 1897.

From 1889 to 1922 there are records of the fluctuations of Utah Lake.[231a] The mean levels of the October-September rainfall years are presented in the accompanying graph (Plate I, f). A small body of water, Utah Lake responds more readily to the variations in the stream flow than does Great Salt Lake. Thus it rose somewhat after the heavy precipitation in 1889-90 and then fluctuated slightly in conformity with the rainfall. After 1899 it dropped in harmony with Great Salt Lake and the mean precipitation of the years 1899-1902.

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[231] Clyde (1931).

[231a] Woolley (1924), Pl. 2.

The Period After 1899

Beginning with 1900 there are data on the stream flow. The runoff graph here presented (Plate II, t) has been obtained from the records of the gauging stations on the Bear River at Dingle (Idaho) (1904-14) and near Collinston (1907-), the Logan River above the state dam near Logan (1914-), the Blacksmith Fork above Utah Power & Light Co.'s dam near Hyrum (1915-), the Weber River near Oakley (1905-) and at Devils Slide (1916-), the Jordan River near Lehi (1914-), the Spanish Fork at Thistle (1909-25) and near Spanish Fork (1904-17), Hobble Creek near Springville (1908-16), the Provo River at Forks (1913-) and near Provo (1905-11), the South Fork of Provo River at Forks (1912-), Cottonwood Creek near Salt Lake City (1905-13), Mill Creek near Salt Lake City (1900-13), Parleys Creek near Salt Lake City (1900-13), and City Creek near Salt Lake City (1900-13). The streamflow records till 1920 are compiled in *U. S. Geological Survey Water-Supply Paper 517*.

The water in the streams is largely derived from the snow that accumulates in the mountains from late October to the end of March. Melting of this snow combined with rains causes the rivers to flood for a few weeks in spring and early summer. Part of the excessive water is stored in reservoirs for release when the rivers are low later in the season or during subsequent summers. Such storage tends to equalize the runoff below the reservoirs. In 1847, on the site of Salt Lake City, the Mormon settlers started the first irrigation system by the white man in North America. Water was diverted from one stream after another, until finally all available water in the region was utilized. Of the 17 stations from which data for the runoff graph were taken, nine record the total flow, or almost the total flow, of the streams, while eight stations are located below one or more important water diversions. Not a single station has been maintained during the whole period since 1900, and of those above large diversions only from three to six have been operated at a time. Although there has been an increase of the diverted water and this must tend to make the curve drop toward the present, a curve that gives practically the total flow (Plate II, u), based on the records of the gauging stations on the Blacksmith Fork, the Weber River near Oakley, and the Jordan River near Lehi, also shows a very similar trend. As in the case of the Humboldt region, the adjusted curve has been given a trend lying exactly between those of the rainfall and the measured stream flow (Plate II, v).

The smoothed runoff and rainfall graphs show a general correspondence; but the former curve undergoes much larger fluctuations, rises in 1913-17 when the rainfall curve drops, and declines more decidedly after 1923. The discrepancies occur because the stream flow is largely determined by snowfall in the mountains above the precipitation stations.

At the beginning of the century rainfall and runoff were at rather marked minima. During the last part of 1905 Utah Lake attained its lowest level for the years 1889-1922 and Great Salt Lake its lowest stand, 4195.8 feet, for the entire period 1845-1933. Precipitation and stream flow increased in 1906, culminating in 1907 and 1909. The lake levels rose from 1907 to 1909 or 1910. During the period 1910-18 the rainfall and runoff were near their average amounts, although they fluctuated somewhat, the former decreasing and the latter increasing. Utah Lake faithfully recorded these variations. Great Salt Lake, however, registered them but faintly, retaining a fairly constant level from 1910 to 1918. In 1919 the precipitation and stream flow dropped to a minimum and the levels of both lakes subsided one to two feet. During the following years the rainfall and especially the runoff increased, and the lakes again expanded. The stream flow had a marked maximum in 1922. Great Salt Lake in 1924 reached its highest stand since 1888, 4205 feet. The runoff decreased quickly after 1922, and in 1924 was only 80 per cent of the average amount. This deficiency together with a very small rainfall during the summer months produced one of the most serious droughts on record in Utah. During the years 1925-30 the measured precipitation did not vary greatly from the average. The stream flow decreased till 1926, when there was a rather severe drought, then it rose to 86 per cent of the normal, remaining there for the three water years 1927-29. With precipitation and runoff decreasing in 1930 and 1931, the water supply during the latter year was the lowest on record up to that time, and streams, springs, flowing wells, and irrigation systems dried. In 1932 the water supply was almost average. Then it decreased again and in 1934 was still lower than in 1931. This was perhaps the culmination of the drought. In 1935 the water supply was somewhat subnormal, in 1936 the average. Great Salt Lake has subsided without marked interruptions since its culmination in 1924. During 1934 it dropped below its 1905 minimum of 4195.8 feet for the period since 1845 and on September 15 was at an elevation of 4194.35 feet. It continued falling and during the autumn of 1935 reached the level of 4193.75 feet. It stood then 17.6 feet below the highest recorded level in 1877.[232]

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[232] I am indebted to Mr. A. B. Purton of Salt Lake City for data on the runoff and on the levels of Great Salt Lake during the last few years.

CHAPTER VI

COMPARISON OF THE REGIONS

Each region here treated is fairly small. It includes mountains, plains, rivers, and lakes, and in each case the mountains are rather uniform in altitude. The separate regions differ from one another in their positions in relation to the cyclonic paths and in the heights of mountains. As a consequence the precipitation in any two regions presents both similarities and differences. For an analysis of these the measured rainfall and the runoff will be compared. The water supplies of the regions may be compared from the " total " plots, given on Plate II, g.

The rainfall curves of Lake County in Oregon and of Modoc and Lassen counties in northeastern California agree fairly well since 1903 and in some respects before that year (Plate II, m. p.). Features in common are maxima in 1904, 1907, 1921, and 1927 and minima in 1898, 1919, and 1924. Discrepancies include opposite trends in the slope of the rainfall curves in 1892-94, 1901, 1909, and 1923. The stream-flow graphs of these regions (Plate II, k, n) agree very well, except for greater general and annual fluctuations in the Oregon curve, the differences being especially prominent in 1911, 1915, 1918, 1920, 1921, 1924, and 1926.

The precipitation graphs of Lake County (Plate II, m) and the Truckee-Carson-Walker region in western Nevada (Plate I, i, j) present somewhat fewer similarities than differences. The curves show a general decline during the eighteen-nineties, then a rise till 1907, followed by a fall till 1919 or 1920. The trends are alike during the last decade. The trends of the curves were opposite in 1892, 1894, 1901, 1902, and 1918 and the amounts of rainfall very different during the years 1903, 1904, 1907, 1909, 1912, 1914, and 1932. The runoff curves match satisfactorily (Plates I, g; II, k). However, the next to the last maximum falls one year earlier in the Oregon graph, and the amounts of water were rather different in the regions in 1910, 1912, 1913, 1923, 1924, 1927, and 1928.

The rainfall curves of Lake County and the Humboldt region present a certain general correspondence since 1903, while differences are mostly in evidence before that year (Plate II, m, s). Noteworthy among the similarities are the maxima in 1904, 1907, 1913-16, and 1922 and the minima about 1909, 1919, 1924, and 1931. The discrepancies include opposite trends during the years 1898, 1899, 1901, 1908, and 1917 and very different amounts of rainfall in the two regions in 1891, 1894, 1902, 1907, 1927, and 1932. The runoff graphs show a good agreement during the period 1912-26 (Plate II, k, q). Then the Oregon curve rises to a new maximum, whereas the Humboldt graph continues its downward trend. Other differences appear in the notably different quantities in 1911, 1915, 1916, 1919, 1921, 1922, 1927, and 1928.

The precipitation curves of Lake County and of the Great Salt Lake basin match rather well since 1910 but differ in many respects before that date (Plate II, m, w). The most noteworthy discrepancies in the amounts of the rainfall occurred during the years 1892-96, 1898, 1902, 1904, 1907, 1909, 1917, 1926, 1927, and 1929. The stream-flow graphs agree with regard to the contemporaneity of the maxima and minima (Plate II, k, t). However, they differ in that the fluctuations of the stream flow are much greater in Lake County and the maxima in the same region were of briefer duration during the nineteen-twenties.

The precipitations in the Great Basin region of northeastern California or Modoc and Lassen counties (Plate II, p) and in the Truckee-Carson-Walker region (Plate I, i, j) agree well except for much more pronounced maxima and minima in the latter curves during the years 1890, 1891, 1904, 1907, 1908, 1914, and 1932 and amounts of rainfall large in one region and small in the other in 1918, 1921, and 1923. The stream-flow graphs match very well, except that the maximum in the early twenties comes one year earlier in the graph for northeastern California and that there are differences in the amounts of water in 1913 and 1915 (Plates I, g; II, n).

The rainfall curves of Modoc and Lassen counties and of the Humboldt region probably present about an equal number of similarities and differences (Plate II, p, s). In common are maxima about 1890, 1907, and 1921, minima in 1919 and 1924, and the trend of the smoothed graphs 1914-25. The greatest difference lies in the relatively high general trend of the Humboldt curve 1898-1908. The precipitation was heavy in one region and light in the other in 1892-94, 1898, 1899, 1902, 1908, 1909 and differed considerably as to quantity in 1905, 1917, and 1932. The stream-flow graphs bear some resemblance, having in common maxima in 1914 and 1921 and minima in 1919 and 1924 (Plate II, n, q). But they also present marked differences, such as the larger seasonal fluctuations in the Humboldt curve and greatly different amounts of runoff in 1911, 1915-20, 1922, and 1926-28.

The precipitation graphs of the northeastern part of California and of the Great Salt Lake basin present about an equally large measure of agreement and disagreement (Plate II, p. w). Both curves have maxima in 1890 and about 1907 and 1921, and both have minima about 1919 and in 1924. After smoothing, the graphs have fairly similar trends. On the other hand, the maximum in 1890 is smaller and those about 1907 and 1921 are more prolonged in the Utah graph. The annual fluctuations are greater in California. The precipitation was heavy in one region and light in the other or of notably different amounts in the two regions in

1890, 1893, 1895, 1896, 1900, 1908, and 1929. The runoff curves show both good conformity and marked differences (Plate II, n, t). The maxima and minima coincide, but the two most recent maxima are much more pointed and of shorter duration in the curve for northeastern California. There are also notable differences in the runoff of the two regions in 1911, 1914, and 1915.

The rainfall graphs of the Truckee-Carson-Walker region and of the Humboldt region present some correspondence during the periods 1871-89 and 1915-32 but mostly differences in 1890-1914 (Plates I, i, j; II, s). The two curves have in common maxima in 1890 and 1907 and minima in 1887 and 1924. The extremes nearly coincide during the decade 1913-22, and the trends of the smoothed graphs are fairly similar after 1914. The most important discrepancies are the pointed maxima in 1890 and 1907 with a deep minimum lying between them in the western Nevada curves as compared with the comparatively low but persistent maximum from 1890 to 1908 in the Humboldt graph. The amounts of rainfall were large in one region and small in the other during the years 1885, 1886, 1892-94, 1898, 1902, 1909, 1911-14, and 1921. Other noteworthy differences in the precipitation were recorded in 1872, 1873, 1877, 1891, 1899, 1904, 1905, and 1927. The runoff curves show both notable similarities and differences (Plates I, g; II, q). In common are most of the fluctuations of the graphs; but the maximum just after the beginning of the century lasted longer in the western Nevada curve, and the fluctuations of the Humboldt curve are much greater. Furthermore, the runoff in the two regions was very different in amount during the years 1904, 1907, 1909-12, 1914-16, 1918, 1921, 1925, and 1932.

The precipitations in western Nevada and in the Great Salt Lake basin present noteworthy similarities but more discrepancies (Plates I, i, j; II, w). In common are maxima in 1890 and 1907 and minima in 1879, 1888, 1902, and 1924. However, the maxima mentioned are more pronounced in the former region, as are also most of the annual fluctuations of the rainfall. Other differences are the better development of the maxima in the Utah curve during the middle eighteen-seventies and eighties and the earlier inauguration of heavy precipitation in the Great Salt Lake region in 1906 and 1920. Furthermore, the rainfall was light in one region and heavy in the other during the years 1873, 1875, 1912, and 1929; and it presented considerable differences as to amount in 1876, 1885, 1890, 1891, 1893, 1895, 1896, 1907, 1910-12, 1914, 1921, and 1926. The stream-flow curves show a good correspondence during the last 20 years, maxima and minima coinciding and the fluctuations being of similar degree (Plates I, g; II, t). The runoff, however, was much greater in western Nevada during the years 1904, 1906, and 1911, prolonging the maximum about 1907. Conversely, the maxima in 1922 and 1927 were of shorter duration in the Truckee-Carson-Walker graphs.

The rainfall graphs of the Humboldt region and of the Great Salt Lake basin match fairly well, most of the maxima and minima coming at exactly the same time and being of similar development (Plate II, s, w). Among the chief exceptions are inverse trends of the two rainfall curves during the years 1872-75, 1877, 1878, 1881, 1892, 1899, 1902, 1909, and 1929; the heavier precipitation in the Great Salt Lake basin in 1909; and the lighter precipitation there in 1892-1905 and 1929. The stream-flow curves also agree rather well (Plate II, q, t), most maxima and minima being in common, and the trend of the smoothed curves being similar except during the years 1914-17 and 1925-27. However, the Utah graph has an unmatched maximum in 1909, and the Humboldt curve has a small maximum in 1925 and another of unknown size in 1910, the year of the enormous flood of the Humboldt. Furthermore, the seasonal fluctuations and the prominence of the maxima and minima are much greater in the Humboldt curve.

Accordingly, the precipitation graphs of the several regions have in common most of the main and a few of the secondary maxima and minima; and the general trends of the smoothed curves agree on the whole. The unsmoothed graphs disagree as regards most of the secondary maxima and minima, and they show several discrepancies due to the correspondence of heavy precipitation in one region with light rainfall in another. Consequently some curves differ from each other in many details. As a whole the different graphs show at best a fair conformity with one another. From 1890 to 1934 the rainfall has been contemporaneously large in one region and small in another during the following number of rainfall years (1 denotes Lake County; 2, Modoc and Lassen counties, California; 3, the Truckee-Carson-Walker region; 4, the Humboldt region; and 5, the Great Salt Lake basin): regions 3 : 4, twelve years; regions 2 : 4, nine; regions 1 : 5, seven; regions 1 : 2, 1 : 3, and 1 : 4, six each; regions 2 : 3 and 4 : 5, five each; regions 2 : 5, four, and regions 3 : 5, three.

The runoff curves as a whole match much better than do the rainfall graphs and in some cases present excellent agreement among themselves. It follows that the precipitation is more alike in the mountains, where the rivers rise, than on the plains.

The precipitation and runoff graphs for the individual regions show very nearly the same degree of correspondence in all cases and present at most a fair conformity.

Although it is a difficult matter to grade agreements, an attempt is made in the following table to show the order of conformity between each rainfall or stream-flow graph and the corresponding curves for the other regions, the order being indicated by that of the figures. After the brackets is given the probable order of correspondence between each region and the other regions with regard to *both* rainfall and runoff:

Lake County, Oregon (1)	Rainfall	2	4	3	5	2	4	3	5
	Runoff	2	4	3	5				
Modoc and Lassen counties, NE California (2)	Rainfall	3	1	5	4	3	1	5	4
	Runoff	1	3	5	4				
Truckee-Carson-Walker region (3)	Rainfall	2	5	1	4	2	5	1	4
	Runoff	2	1	5	4				
Humboldt region (4)	Rainfall	5	1	2	3	5	1	2	3
	Runoff	1	5	2	3				
Great Salt Lake basin (5)	Rainfall	4	2	3	1	4	3	2	1
	Runoff	3	4	2	1				

Only in the first group is there the same order of correspondence of rainfall and of runoff. Northeastern California forms a connecting link between Lake County and western Nevada. The Humboldt region and the Great Salt Lake basin are rather closely allied.

The best conformity between the rainfall curves seems to be shown by the following combinations and in the given order: 2:3, 4:5, and 1:2; and the best detailed agreements between the stream-flow graphs appear to exist in these combinations and in this order: 1:2, 2:3, 1:4, and 3:5.

The numerous small discrepancies among the regional rainfall curves and more particularly the compensating rainfall (i. e. light in one region, heavy in the other), which tends to even out regional deficiency and excess, indicate the advisability of selecting small and homogeneous regions for climatic study, if, as in this case, local applicability is desired. The use of small regions and the October-September precipitation has given gradings for the relative aridity or humidity of certain years that differ from those computed by Henry,[233] Russell,[234], and Hoyt,[235] who employed states or even larger regions and based their studies on the January-December rainfall.

[233] Henry (1931).

[234] Russell (1932), 262-264.

[235] Hoyt (1936).

CHAPTER VII

THE MAIN RAINFALL FLUCTUATIONS AND THEIR SIGNIFICANCE

The prominent maxima and minima of the combined mountain and plain precipitation occur in all or most of the regions under discussion, as shown by a comparison of the "total" plots for the period since 1840 (Plate II, g).

From 1801 to 1828 wide tree rings indicate ample precipitation in the northwestern part of the Great Basin (Plate I, c, e). Also, judging from the tree growth the precipitation was exceedingly small in 1829 and then increased to a fair maximum in 1836-38. Then followed, during the eighteen-forties, a widespread and persistent drought, in severity comparable to that of 1924-34. About 1850 the precipitation was on the increase and reached a climax in most regions in 1853. After that it decreased rather generally for a few years to below the average and then rose to a marked culmination in 1862. The rainfall dropped in 1863 and 1864 and thereupon increased to one of its most prominent recent maxima in 1868, only to fall again till 1871. During the eighteen-seventies and the first part of the eighties the precipitation fluctuated from year to year, showing no decided tendency toward either a general increase or decrease. Little or no correspondence prevailed between the separate regions. In 1884 the precipitation was generally ample. Thereafter it diminished to a prominent minimum and a severe drought that culminated in 1889. During the following winter it abruptly swung to an unusual maximum, to remain above the average in most regions till 1897, although fluctuations and a general decline occurred. A moderate minimum followed, about 1900. Thereupon the rainfall increased during a few years to attain in 1907 a maximum which was somewhat more prominent than that of 1890 and perhaps surpassed that of 1868. On the whole the precipitation has decreased from this culmination in 1907 to the present. About 1910 the rainfall differed in the several regions, but in 1914 it had a small general maximum and then diminished to a rather marked minimum in 1918-20. Thereafter it increased abruptly to its latest prominent maximum in 1921 and 1922 and then almost as quickly dropped to a very low minimum in 1924. During the years 1925, 1927, and 1932 the combined precipitation of the mountains and the plains was not far from the average; but during the remaining years of the period 1924-34 the precipitation of the mountains was subnormal, causing, in combination with the cumulative effect of the decrease in rainfall since 1907, a drought that had its only known modern counterpart during the eighteen-forties. The measured rainfall gives barely a suggestion of the drought, which manifested itself in the paucity of the runoff and the very low stand or desiccation of rivers, lakes, and reservoirs. During 1935 a change took place. In all the regions taken together the water supply in the rainfall year 1935 was about 95 per cent and in 1936 about 112 per cent of the normal.

A comparison of the rainfall since 1850 with that during a few preceding centuries is afforded by tree-growth curves for Susanville and Lakeview and by plots marking drought periods (Fig. 7; Plate I, c, e, k).

According to the Sunsanville ring curve (Fig. 7) the precipitation since 1850 has been of the average amount. It was greater than at any time after 1850 during the years 1526, 1537-40, 1661-63, 1666, 1674, 1801, 1804, and 1811, the period 1801-13 being the wettest of its duration recorded. The precipitation seems to have been smaller than during any year since 1850 (the ring of 1924 is 0.35 mm. wide [235a]) in 1776 and 1777, and it may have been very light (rings less than 0.5 mm. wide) in 1498, 1500, 1501, 1533, 1580, 1629, 1655, 1703, 1783, 1787, and 1829. The drought periods of 1776-89 and 1621-48 were probably more severe than that of 1924-34.

According to the Lakeview ring curve (Fig. 7) the rainfall since 1850 has been above the average, and the 67-year period 1851-1917 may have been moister than any equally long period since 1455. The precipitation seems to have been greater than at any time after 1850 in 1524, 1525, 1559, 1613, and 1791. It appears to have been lighter than at any time since 1850 (the ring of 1924 is 0.35 mm. wide; Pl. I, e) in 1532, and it was very light (rings less than 0.5 mm. wide) in 1501, 1508, 1528, 1529, and 1783. The drought period beginning 1918 is the most severe recorded, that of 1840-50 being second.

Also, according to the drought plot shown on Plate I, k (based on 4 trees from Fort Bidwell, California, and 16 trees from Lakeview, 4 from Paisley, and 3 from Silver Lake, Oregon, and drawn from a detailed plot prepared by Schulman and Hale), the drought beginning 1918 was most severe, that of the eighteen-forties being next. According to Hardman and Reil's [236] ring curves from the upper Truckee region the period 1875-1917 was the wettest of its duration since 1540, though in actual moisture it was surpassed by the period about 1600-20. The supposed bearing of submerged trees in Eagle Lake and Lake Tahoe on the relative rainfall previous to and since 1850 has already been discussed (pp. 26 and 37).

These fluctuations of the precipitation during the past 100 years, it may be restated, represent the actual water supply, as judged from or directly given by the available data. Because of the heterogeneous nature of the records and because on the whole they increase in quality and quantity towards the present, especially the earlier and the later parts of the " total " plots are not fully comparable. As seen in the " grand total " plot, in the smoothed curve prepared from this plot, and in the smoothed curve constructed from the summary plots of Lake County, Modoc and Lassen counties, and the Truckee-Carson-Walker region the general fluctuations vary considerably in length, amplitude, and shape (Plate II, h, i, j). They are clearly not due to a recurring simple cycle, even if cycles be liberally defined to include both systematically recurring fluctuations of similar amplitude and shape and those that vary in length, amplitude, or form, or in all three characteristics.[237] They may, however, represent a composite of cycles which at times reach independent maxima and minima and at other times interfere, two or more in number producing crests and troughs of different duration, amplitude, and shape. Although, strictly taken, the records may be too short and too inaccurate for predictions, which should be based only on records showing repeated systematic recurrence,[238] an attempt, nevertheless, will be made to project the finally obtained curves a few years into the future.[239] But first some general points will be touched upon.

[235a] Since the curves shown in Figure 7 have been smoothed they do not, of course, indicate the actual ring widths for individual years.

[236] Hardman and Reil (1936), 27-28.

The characteristics of the past rainfall fluctuations give hints regarding future swings. The transition from deficient to ample precipitation is commonly abrupt. The precipitation rises from a minimum to a maximum usually in two to four years. The extremely dry summer of 1889 was followed by an extraordinarily stormy winter. Occasionally and regionally the increase in rainfall is gradual, as in Utah between 1902 and 1907. A very heavy precipitation lasts mostly for but one year while a more moderate rainfall, forming a maximum, frequently prevails for two or three successive years. In some cases the rainfall maxima are broken by a year of moderate or light precipitation, and in other cases they consist, rather, of two or more semi-independent maxima. The duration of the crests of the precipitation maxima thus ranges from one to about five years. Some precipitation maxima end as abruptly as they begin, others taper off.

The transition to the rainfall minima is abrupt about as often as it is gradual. Very pronounced minima usually last one year, rarely two or three successive years, while minima of smaller amplitude may persist for about four years. The rainfall minima thus agree in most respects with the maxima. They differ in some regions, however, in that they display smaller amplitude, rarely falling below 50 per cent of the average rainfall, whereas the maxima sometimes surpass 200 per cent.

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[237] Clements (1929); Marvin (1929); see also " Remarks by H. H. Clayton " in Carnegie Institution of Washington: Reports of the conferences on cycles (1929), 71-72.

[238] Ward (1926).

[239] The cyclic sunspot curve cannot be used as a tool for prediction, for the deduced rainfall fluctuations show no evident relationship to the fluctuations of the sunspot numbers. Douglass (Tree growth, 1933, 486; Climatic cycles, Vol. 3, 1936, 116-126) found some correlation between tree growth in the Southwest and the sunspots, Clements (1929, 65; Clements and Chaney, 1936, 45) between droughts in the West and the major sunspot maxima, and Streiff (1926, Fig. 3; 1929, 408-410) and Shuman (1931, 100, Fig. 5) between the fluctuations of Great Salt Lake and the double sunspot cycle, but the last two relationships have not held during the recent drought.

The spacing of the general maxima and minima depends somewhat on which fluctuations are regarded as being prominent enough and of sufficiently widespread occurrence to be considered. In the "grand-total" plot and its smoothed curve (Plate II, h, i) a selection has been attempted on the basis of the known facts, without considering any possible cycles that may have been subdued or neutralized by interference. The most important, though by no means equal, rainfall maxima seem to be those culminating in 1853, 1862, 1868, 1884, 1890-93, 1907, 1914, and 1921, and possibly the ones that reached climaxes in 1876 and 1927 should also be included. The most important and general minima are those of the eighteen-forties, 1864, 1871, 1889, 1898, 1918-20, 1924-26, and 1931-34, to which should possibly be added those of 1858, 1879, 1903, and 1912. The maxima are consequently spaced at intervals of 6 to 17 years, most of the intervals being 6, 7, or 8 years. The intervals between the minima range from 5 (3 in unsmoothed curves) to 21 years, but are frequently 6 to 7 or an even multiple of this. Thus there has been for the most part a swift succession of dry and wet times. The short waves are superimposed on longer oscillations, notably those of 1868 to 1890, 1890 to 1907, 1907 to 1921, 1907 to an unknown date, and 1921 to an unknown date, which prevailed for 22, 17, 14, about 20(?), and about 16(?) years, averaging 18(?) years. These greater swings present long general declines and brief sharp increases of the rainfall; declines from 1868 to 1889, 1890 to 1903, 1907 to 1920 or 1934, and 1921 to 1934, lasting for 13 years in three cases, 21 years in one case, and 27 in another.

Attempts at prediction may be made with the aid of the smoothed graph of all the regional summary plots after 1886 (Plate II, i). The climax interval 1868 to 1890 is not used, because it differs from the comparable later ones in its longer duration and in having two secondary maxima, in 1876 and 1884. The curve sections 1887-1909, 1904-26, and 1918-34 have been superimposed on one another with the climaxes of 1890, 1907, and 1921 as the common starting point (Plate I, x). The mean of these three curves has been constructed, and, after the termination of the 1918-34 section, this mean has been extended by the weighted average of the two remaining sections. This latter, dash-and-cross curve—prediction 1—would indicate the probable water supply of the studied regions for the next few years.

In another attempt at prediction (Plate I, y) the average curve just obtained from the sections 1887-1903, 1904-20, and 1918-34 has been copied and the end given the date 1934 as in the previous case. Thence the curve has been repeated as a broken line. The maxima are thus placed 16 years apart, which is the probable average length of the intervals between them. Again, the broken curve—prediction 2—would give a suggestion of the probable moisture conditions during the next coming years.

In prediction 1 the water supply is barely above the average in 1935 and is somewhat greater in 1936. This is about 8 per cent too high and approximately correct, respectively, for the two years: the available water in 1935 was about 95, in 1936 about 112, per cent of the normal. In prediction 2 the water supplies in 1935 and 1936 are some 20 and 12 per cent too low, respectively. The actual amounts are marked by a dotted line. According to both predictions there should be a water maximum in 1936 or 1937, then a decrease in the supply, reaching a minimum about 1948 or 1949, and finally an increase to another maximum in 1951, 1952, or 1953. The prominence of the present, or soon coming, maximum may suggest whether the next decade will have a larger or smaller water supply than the average. It should be repeated that the projected curves give only hints of the future water supplies, for the cycles (if this term be permitted) upon which the predictions are based are only three, and all differ in length, amplitude, and shape. Since the 1924-34 drought was surely the only one of its severity since the eighteen-forties, its equal may not recur for several decades.

PART II

TREE GROWTH IN RELATION TO RAINFALL

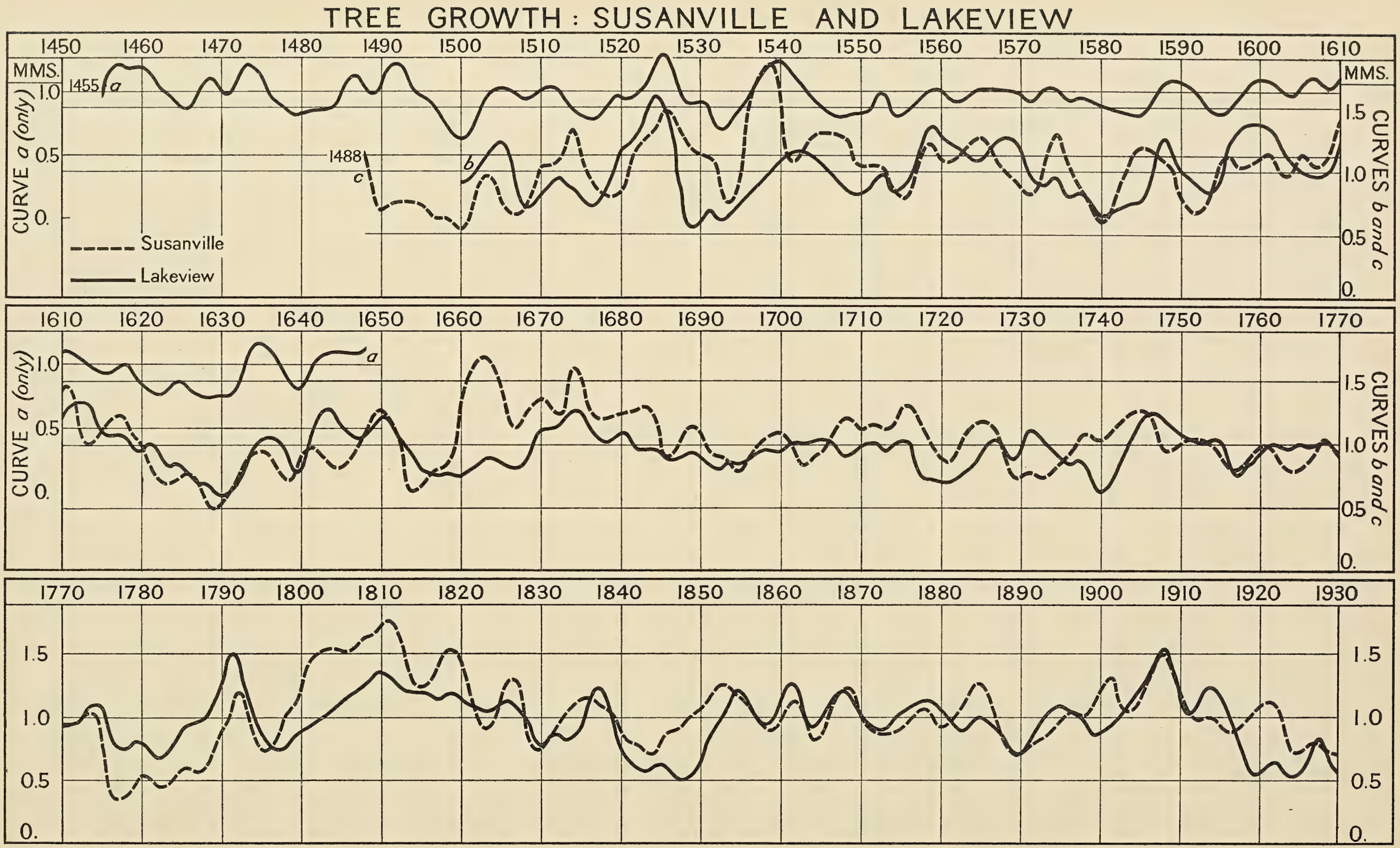

Fig. 7—Tree-growth curves for Susanville, California, 1488-1930, and Lakeview, Oregon, 1455-1930. Smoothed mean-growth curves of individually standardized specimens, prepared by Messrs. Edmund Schulman and Thomas Hale. Curve *a* (supplementary curve for Lakeview): the part for 1455-1492 is based on one specimen, the latter part on six specimens. Curve *b* (Lakeview): the part 1500-1536 is based on one tree, the part 1537-1594 on two to seven trees, the part 1595-1656 on eight trees, and the part after 1656 on 14 trees. Curve *c* (Susanville): the part 1488-1630 is based on one tree; the part since 1630 on five trees.

CHAPTER VIII

FACTORS OF GROWTH AND EARLIER STUDIES

As a part of the investigation of rainfall fluctuations in the Great Basin during the past one hundred years, tree-ring samples were collected by the writer in 1931. Radial cuts of triangular cross section[1] were sawed from 100 tree stumps near the dry or lower limit of the forest in northeastern California and south-central Oregon. This material makes possible a special study of the relationship between precipitation and tree growth along the line of junction of forest and semidesert. The wood samples have been kindly examined by Professor A. E. Douglass and his assistants Mr. Edmund Schulman and Mr. Thomas Hale to whom the writer extends his sincere thanks. These gentlemen measured the growth rings, standardized the individual ring graphs,[2] and made averaged final plots. They prepared a growth curve from Susanville, California, beginning with the year 1485; another curve from Lakeview, Oregon, beginning with 1500; and a supplementary graph from Lakeview covering the period 1453 to 1650. These curves, as smoothed, are shown in Figure 7. They also constructed a plot for the time after 1500, which shows narrow growth rings in 27 trees from Fort Bidwell in California and from Lakeview, Paisley, and Silver Lake in Oregon (simplified for the period 1650-1930 in Plate I, k [2a]). The remaining tree samples were not used, either because they presented too small variations in the width of the rings, had too narrow rings, or were believed to be affected by insect ravages, or else for other reasons.

As already explained in the Introduction the accompanying precipitation graphs show the rainfall for " rainfall years " beginning with October and ending with September; by " the rainfall of 1901 " is understood the rainfall of the 12-month period October 1900-September 1901. The tree ring of 1901, of course, was formed during the spring and summer of that year. The tree-growth curves have been smoothed twice in the same manner as have the rainfall and runoff graphs.

The growth of trees is usually determined by a complex of interacting factors and conditions.[3] Most important among these are the climatic conditions and the quantity of food materials stored in the wood. The principal climatic factors are: (1) water supply or soil moisture of the current season, its amount and time distribution; (2) temperature, especially the duration of favorable temperatures and the range of fluctuation during the normal growing season; (3) light, as a necessary factor for photosynthesis; (4) humidity and cloudiness, as controlling factors of transpiration; and (5) quality of the sunlight, as changing with the number of sunspots. "A favorable season would be one in which the soil moisture would be adequate, the temperature range within the limits of growth, and the illumination sufficient for photosynthesis, while the relative humidity would be such as to prevent excessive transpiration."[4] With an adequate water supply the amount of wood formed in a tree would depend on its total leaf surface, the duration of illumination, and temperature.[5] "There is rarely justification for attributing inequalities of growth under natural conditions to the fluctuations of a single environmental condition. So complex is the interaction of the several conditions that the fluctuations of one must always be interpreted or investigated in terms of the others."[6]

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[1] Douglass, Climatic cycles, Vol. 2 (1928), 21.

[2] *Ibid.*, 41.

[2a] On the graph (Plate I, k) the vertical lines indicate the number of trees (out of the 27) with narrow rings during the individual years.

[3] MacDougal (1924), 8, 45, 81; Shreve (1924), 106, 107, 112, 114, 116; Antevs (1925), 120-133, 139-140.

Extremes of the climatic factors, such as too little or too much water and light or too low or too high temperature, may only check growth or else they may induce wilting, root suffocation, sunburn, frost injuries, heat canker, etc.[7] Excessive snow, sleet, and wind may cause breakage. Lightning and fire may bring about injuries. Wounds, even if small, formed by any of these agencies may become serious by forming centers of infection for fungi.

The importance of individual factors varies with conditions. In the semiarid regions of the West, where periods of inadequate water supply may occur during a growing season that is favorable with regard to temperature, scarcity of water may dominate the situation and largely determine the amount of growth.[8] MacDougal gives examples of trees that began growing only after the coming of the spring or summer rains or that stopped growing during dry and hot spells in the summer.[9] This applies to most conifers at or near the dry limit bordering the semidesert.

The relationship between rainfall and tree growth in regions of differing precipitation in the West has been studied by Huntington, Douglass, Shreve, MacDougal, W. S. Glock, and others. Huntington[10] has compared the growth of the giant redwood or sequoia (*Sequoia gigantea*) at Dillonwood, south of the Sequoia National Park, California, with the rainfall at Porterville (alt. 464 ft.), some 35 miles to the west and at a level of about 6000 feet lower. He has also analyzed the growth of the sequoia at Hume, three miles northeast of the General Grant National Park, in relation to the precipitation at Fresno (alt. 327 ft.) and (before 1882) at San Francisco (alt. 155 ft.), both of these cities being about 6000 feet lower, the former 50 miles to the west and the latter 200 miles to the northwest (see Fig. 1, p. 6, above).

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[4] MacDougal (1924), 45.

[5] MacDougal (1936), 222.

[6] Shreve (1924), 106.

[7] Hubert (1930).

[8] Shreve (1924), 106.

[9] MacDougal (1924), 9, 44, 88.

[10] Huntington (1914), 161, 163; (1925).

Douglass [11] has examined ring curves of yellow pines (*Pinus ponderosa*) growing at distances from one to ten miles from Prescott, Arizona, in relation to the rainfall there; also yellow pines growing near or within sixty-five miles of Flagstaff, Arizona, in relation to the precipitation at Flagstaff. Lately Douglass and Glock [12] have studied the relationship between the growth of some sixty trees from various parts of the area centering on the Chuska Mountains, 30 miles south of the northeastern corner of Arizona, and the rainfall at Prescott, Flagstaff, and Natural Bridge, 240 and 175 miles to the southwest and 55 miles to the south of the Chuska Mountains, respectively. Douglass has, furthermore, compared the growth of five giant sequoias at Hume with the rainfall at Fresno and San Francisco,[13] with that at San Francisco alone,[14] and with Lynch's rainfall indices, 1770 to 1930, for the Los Angeles area, including San Diego records after 1850.[15] Douglass has finally compared a ring curve from sixteen pines growing at 6000 feet elevation in the San Bernardino Mountains northeast of Redlands, or 70 miles due east of Los Angeles, with the mentioned rainfall indices and records for Los Angeles and San Diego.[16] The curves are published on such a minute scale as to be very difficult to read, but the correlation coefficient is +45 per cent, with a probable error of 5 per cent.

Shreve [17] has analyzed the relationship of the radial increase of a Monterey pine (*Pinus radiata*) growing seven miles from Carmel and ten miles from Monterey, California, and of a coast redwood (*Sequoia sempervirens*) growing 17 miles from Carmel and 20 miles from Monterey with the rainfall at Monterey and Carmel. He has also compared the ring widths of ten Monterey pines growing close to the Carmel rainfall station with the local precipitation record. MacDougal [18] has measured by dendrograph the increase in girth of Monterey pines and of coast redwoods near Carmel, California, and has compared the growth graphs thus obtained with precipitation and soil moisture. With an unfailing supply of ground water, the graphs for trees of both kinds were found to be without correlation with the precipitation curves, or even to record the greatest growths during years of minimum rainfall.

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[11] Douglass: Climatic cycles, Vol. 1 (1919), 27-29, 65-67; Vol. 2 (1928), 67, 72, 97-102.

[12] Douglass: Climatological researches (1933), 208-211; Climatic cycles, Vol. 3 (1936), 14.

[13] Douglass: Climatic cycles, Vol. 1 (1919), 71.

[14] *Ibid.*, Vol. 2 (1928), 100.

[15] Douglass: Tree Growth (1933), 482, 489.

[16] *Ibid.*, 482, 486, 489.

[17] Shreve (1924), 106-114.

[18] MacDougal (1929); (1936), 222, 245-249.

Jessup[19] has obtained a fairly good relationship between the ring curve of four junipers growing from 5 to 45 miles from Burns, southeastern Oregon, and the rainfall at and near Burns. On the other hand Bonner[20] has found a conformity of only about 60 per cent between the growth of yellow pines and giant sequoias, measured by Douglass and Huntington in the Sierra Nevada, and the rainfall in the Sierra Nevada region. On the eastern slopes of the Sierra Nevada north of Lake Tahoe, Hardman and Reil[21] have measured the rings of numerous yellow pines in the lower forest zone at elevations of from 5500 to 8000 feet, where the precipitation comes largely during the winter months and in the form of snow. They have found a good agreement between tree growth and stream discharge but not so good a relationship between tree growth and precipitation at the weather stations, which are all far from the sampled trees.

These are the existing analyses of the relationship between precipitation and tree growth in the West. More detailed investigations are necessary before reliable conclusions about past rainfall conditions can be drawn from the varying widths of growth rings in regions of small rainfall; and studies are necessary to determine the special relationship in each case or region. The evaluation of the influence of a single factor, rainfall, on a growth that is actually determined by a group of interacting conditions should be made with due consideration for the findings of biologists and with realization that trees are not lifeless instruments or rain gauges.

Of the trees here mentioned, the most debated rainfall recorder is the giant sequoia, which grows at altitudes of between 5000 and 7000 feet on the western slopes of the Sierra Nevada far from and high above the meteorological stations. In the writer's[22] opinion its growth has generally but a small direct relationship to the precipitation. The precipitation comes largely as snow, and such trees as have a sufficient water supply even during dry years may be retarded by excessive snowfalls, which imply a late spring and a short growing season. These views are supported by Fry and White,[23] who hold that the sequoias as a rule make their greatest growth during long and warm seasons following upon winters with little snow.

Trees growing on the border of the desert are generally more dependent on the water supply than on all other factors, and their growth increases and diminishes with the amount of water available during the growing season. The fluctuations of moisture and of growth, however, are not proportional. The width of the rings is only an approximate measure of the degree of aridity. Far more wood is formed per inch of rain in dry years than in wet ones,[24] perhaps chiefly because much more water runs off and is lost for the tree during rainy seasons.

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[19] Jessup (1935).

[20] Bonner (1935).

[21] Hardman and Reil (1936), 14, 25.

[22] Antevs (1925), 129.

[23] Fry and White (1930), 39-41.

The cyclic changes in the number of sunspots [25] may affect tree growth directly by the accompanying changes in the composition of the sun's rays and indirectly by the influence they exert on precipitation, temperature, and other climatic factors. The relationship between the sunspot curve and tree-ring graphs is very dissimilar in different regions.[26] Of the 12 principal growth maxima since 1800 in the writer's Susanville curve and the 13 in the Lakeview curve 11 of the total of 25 coincide with decreasing numbers of sunspots, 7 with minima, 4 with increasing numbers, and 3 with maxima of sunspots. Of the 25 corresponding growth minima 10 coincide with minima of sunspots, 6 with maxima, 5 with increase, and 4 with decrease in the number of sunspots. Thus in these instances decreasing activity of the sun seems to favor growth, while minimum, increasing, and maximum activity of the sun seem to retard growth. The discrepancies between rainfall and tree growth at Susanville and Lakeview have no decided relationship to the number of sunspots.

Accidental local changes and local differences in precipitation seem at times to affect the amount of growth, as the following analysis shows. The writer's tree-ring curves for Susanville and Lakeview may be said to disagree with respect to any year for which the ring widths for the two localities differ by more than 0.2 millimeter. On this basis they disagree since 1890 in 1894, 1899-1902, 1911, 1913, 1916, 1918-21, 1923, and 1926. By eliminating from this list such discrepancies as appear to be accounted for by differences in the precipitation at Susanville (or Fort Bidwell) and Lakeview—those in 1894, 1911, 1920 and 1921—and by further eliminating such differences as seem to be referable to the time distribution of the rainfall and to temperature conditions, as discussed in later sections of this paper, there remain those in 1900, 1901, 1918, 1919, and 1926. All of these represent growth near Susanville that was excessive in relation to the measured rainfall at Susanville and Fort Bidwell—growth, however, that might have been due either to local changes prevailing during those years or to precipitation relatively greater at the site of growth of the trees than at the meteorological stations. A highly probable local change would be liberation by thinning of the forest, giving the trees access to more water, light, and nourishment; but it is unknown whether or not this was the actual cause.

Another accidental factor of growth, viz. injurious insects, is of sufficient importance in the northwestern Great Basin to deserve attention.

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[24] Shreve (1924), 114.

[25] Wolfer (1902, 1920, 1925); Brunner (1931, 1933).

[26] Douglass: Tree rings (1931), 303-312; *idem:* Evidences (1933), 355; Glock (1933).

While there are more than a hundred different kinds of injurious insects known to feed on the western yellow pine alone, the most important insect groups in the present connection are (1) the pine bark beetles (*Dendroctonus*) which bore between the bark and the wood and seriously injure or kill the trees; (2) various moths and butterflies whose caterpillars either partially defoliate the trees, retarding or stopping their growth until the needles are replaced, or else, though less frequently, devour all of the needles and kill the trees; and (3) the bark weevils (*Pissodes*) which injure branches, twigs, and terminal shoots.[27]

Because of damage caused by insects, lightning, fire, frost, intense heat, excessive snow, sleet, and wind, etc.,[28] caution must be used in referring narrow growth rings to drought alone. Discretion is the more necessary since dry seasons, when the vitality of the trees is at a low ebb, seem to favor development of certain species of injurious insects, notably the western pine beetle, which further check growth, already deficient because of drought. When data on rainfall are lacking, the reductions in growth mentioned are in most cases not easily distinguished from those caused by drought, although narrow and defective rings due to accidents at times may be differentiated, because they tend to increase the prominence of the shorter cycles in the growth curves,[29] or are distinguishable in other ways.[30]

[27] Keen (1929), 10-14, 1-33, 40, 69.

[28] Hubert (1930); Craighead (1927).

[29] Douglass: Tree growth (1933), 493, 494.

[30] MacDougal (1936), 250, Plates 1-5.

CHAPTER IX

OBSERVATIONS AT SUSANVILLE, CALIFORNIA

Radial wood samples for ring measurements were sawed from stumps of yellow pine (*Pinus ponderosa*) in the hills about three miles north of Susanville, on the edge of the Great Basin in northeastern California. The locality lies at an altitude of about 6000 feet and a few miles west of the dry limit of the forest along the semidesert to the east. The trees grew on a very steep, dry slope covered with cobbles and boulders of lava. The five trees used in compiling the published graph ranged in age from 295 to 445 years. They were cut in the summer of 1931. Climatological records have been kept at Susanville (elevation, 4195 feet) during the years 1888-1918 and since 1927.

The smoothed graphs of the widths of the tree rings and of the October-September precipitation at Susanville do not show any noteworthy correspondence during the period 1889-95 but present a fairly good general agreement with one another from 1896 to 1916 (Plate I, b, c). They differ after 1895 in that the growth maxima about 1900 and 1908 are more pronounced and the latter maximum follows one year after the corresponding rainfall maximum.

In order to insure an objective comparison of the unsmoothed curves, the deviations from the horizontal lines are considered. In the rainfall curve the horizontal line marked 100 per cent represents the average for the period of record. In the growth curve the line marked 1 millimeter represents a ring thickness of 1 millimeter, which happens practically to coincide with the average. When, on the scale of the graphs, the deviations from the average lines differ by more than 5 millimeters, we speak of disagreement between tree growth and rainfall. According to this standard the growth was relatively excessive in 1899-1902, 1905, 1908-10, and 1915. It was deficient in 1890, 1893, 1895, and 1904. In 1890 the tree growth was at a minimum, while the rainfall was at a maximum. The precipitation was excessive during all the winter months and came largely in the form of snow, but it was subnormal in April and during June-September. Of course, it is not to be expected that the growth would fully match the sudden increase in precipitation, especially as the time distribution of the rains was very unfavorable; but its complete failure to respond speaks for inability of the trees to avail themselves of the water supply. Since the precipitation during the rainfall year 1889 was but little below the average, and the rainfall in May and

June was excessive, that year should not have had any retarding aftereffects on the growth in 1890. There are no records of the precipitation during the previous years. The growth was perhaps checked by insects. The discrepancy between growth and rainfall was also marked in 1893. However, the excessive precipitation occurred during November and December (1892) and fell as rain, while the total precipitation of January-May equalled the normal amount, and only a trace of rain came during June-August. The small growth may be due largely to this exceptionally unfavorable distribution of the rainfall and to the heat of the summer checking the growth by inducing too free transpiration.

In 1895 the growth was distinctly deficient in relation to the rainfall, which was considerable because of unusually heavy snows and rains in December (1894) and January. On the other hand, the total precipitation during February-May was somewhat subnormal, and there was only a trace of rain in June and July. Furthermore, these latter months were very hot. The growth may therefore have matched the available water supply. During the years 1899-1902 the tree growth was more or less excessive in relation to the annual precipitation. The first year the rainfall was above the normal only in the months of March, May, and August; but this favorable time distribution of the rain and the relatively low summer temperature perhaps suffice to explain the wide ring. In the water year 1900 the month of October (1899) had excessive precipitation; November, December, and March had somewhat more than normal rainfall; and July had 0.63 of an inch, or nearly three times its average amount.

The large growth can hardly be explained by this July precipitation and the relatively low temperature in August; for all the months not enumerated had subnormal rainfall, and so had the preceding season. It was perhaps due to thinning of the forest or to precipitation that was relatively heavier at the site of growth than at Susanville, as suggested above. The slightly excessive growth in 1901 may also have been a consequence of conditions other than precipitation and temperature as measured at Susanville, for the favorable and unfavorable tendencies of these two factors about balance each other. The ring width in 1901 shows a decrease from that in 1900, while the precipitation shows an increase. The reasons are not obvious. Both the winter and the spring precipitations were greater in 1901 than in 1900; and, while July 1900 brought 0.63 inch of rain, August 1901 brought 1.77 inch. The heavy growth this year had perhaps the same cause as that of 1900. The relatively wide ring in 1902 cannot be due to the distribution of the precipitation, which was on the whole unfavorable, but is perhaps in part referable to the comparatively cool weather in July and August. The winter precipitation was somewhat subnormal and mostly in the form of rain:

the spring rains were also less abundant than usual; June was rainless and August nearly so, while July had more than twice its normal amount.

The failure in 1904 of the growth to match the relatively heavy precipitation may be explained by the unfavorable time distribution of the moisture. There were abundant snows and rains in November (1903), February, and March, but the spring and summer were rather droughty. The deficiency in moisture was not offset by the comparatively low summer temperature. On the other hand, the relatively marked growth in 1905 cannot have been due to the time distribution of the rains, for this was unfavorable, the spring and summer months being droughty. In fact, the spring and summer rainfall of 1905 was much like that of 1904, while the winter precipitation was considerably smaller than that of the preceding winter. In spite of this the tree growth was greater in 1905. A favorable factor of growth in both years was the low summer temperature, but this alone cannot account for the excessive growth in 1905 which must have been considerably influenced by factors other than precipitation and temperature.

A pronounced maximum of growth in 1908 corresponds to a slightly subnormal precipitation. The rainfall was relatively heavy only during the months of December (1907) and May, and the temperature during the summer months was about normal. It is probable that the water table was high after the rains of the water year 1907, that the trees had a substantial storage of food material, and that these two factors contributed much to the heavy growth; but they can hardly have been the only reasons. The smaller excesses of growth in 1909 and 1910 occurred in spite of subnormal precipitation during the spring and summer months. Whether or not this, too, is referable to the heavy rainfall of 1907 cannot be determined.

The diameter growth and the precipitation in 1913 and 1914 are instructive, since the ring widths were 1.2 mm. in 1913 and 1.0 mm. in 1914, while the amounts of the annual precipitation were alike. The chief cause of the discrepancy may be the distribution of the rainfall. In 1913 the winter precipitation was somewhat subnormal, but the summer rainfall was much above the normal. The rainfall of June and July was fully four times the average. In 1914 there came very heavy snows in the middle of the winter; but there was a deficient rainfall in the spring and practically no rain in the summer. In addition, the temperature was very high from March to September, checking the growth. The favorable effect of the heavy summer rainfall in 1913 is the more evident when the deficiency in moisture in 1912 is taken into account. In 1915 a ring of average width was formed during a year of definitely subnormal precipitation at Susanville. While the ring width was the same as in 1914, the precipitation was only 11 inches as compared with 24 inches during 1914.

To be sure, the total rainfall of the months April-August was more favorable in 1915, amounting to 3.32 inches as against 1.86 inches during the same period in 1914, but the bulk of this rain in 1915 came in May, while the months of June and August were rainless. The comparatively wide ring in 1915 was perhaps due to heavier precipitation at the site of the trees, for the runoff in 1915 was well above the average, suggesting relatively greater precipitation in the mountains.

The precipitation curve (Plates I, b ; II, p) for the part of northeastern California that belongs to the Great Basin (Alturas, Cedarville, Fort Bidwell, Madeline, and Susanville) corresponds in almost every detail with the rainfall curve of Susanville and may therefore be used for comparison of radial tree growth and rainfall since 1916. The smoothed curves of the Susanville tree growth and of the regional rainfall agree on the whole after 1918, though the growth maximum about 1921 is more pronounced and that about 1926 less pronounced than are the contemporary rainfall maxima. During the period 1916-18 the smoothed curves trend in the opposite directions, since the tree growth began to increase, while the annual rainfall was still diminishing.

The unsmoothed curves disagree in 1918, 1919, 1922-27, and 1931. The growth was relatively excessive in 1918, 1919, 1923, 1926, and 1931 and was relatively deficient in 1922, 1924, 1925, and 1927. In the following detailed discussion precipitation and temperature data from Fort Bidwell and Madeline are used. In 1918 the growth was normal, though the precipitation was subnormal during every month except the last of the rainfall year, when the growth may have stopped. Furthermore, the growth increased over that in 1917, whereas the rainfall decreased. If these conditions of precipitation at Fort Bidwell hold for the growth site near Susanville and if the precipitation was not relatively heavier there, the growth can be explained by thinning of the forest, as suggested in the preceding chapter. In 1919 a comparatively heavy growth was achieved, although the total precipitation was small and the summer was practically rainless and somewhat warmer than usual. The heavy growth was all the more clearly unrelated to the recorded precipitation, as the rainfall of the preceding year was still smaller. The wide ring can be attributed to the same causes suggested for 1918. The deficient growth in 1922 may have resulted chiefly from the subnormal rainfall during the spring and summer months and from the rather high summer temperature, though one might expect that moisture and food material conserved from the previous year would have effectively counteracted the drought.

This narrow growth ring following immediately after a year of exceptional rainfall shows that the effects of good years in conserving moisture and food material can be over-estimated. While the precipitation in 1923 was slightly less than that in 1922, the ring was twice as wide. The growth may have been favored by the heavy rainfall in June and by the relatively low temperatures in June, July, and August; but this cannot be the full explanation, for, among other things, the winter precipitation was deficient and little food material could have been stored during the previous year. The exceedingly small growth in 1924 occurred during a very dry summer following upon a winter of deficient precipitation; yet growth was smaller than seems warranted by the drought and the somewhat high summer temperature, especially since the preceding summer produced such a wide ring. Perhaps it was partly caused by ravages of insects. The deficient growth in 1925 may have been partly an aftereffect of the bad year 1924 and partly a consequence of the high summer temperature.

The growth in 1926 was large, although the precipitation was deficient during every month from November (1925) to October and the summer months were more than usually warm. It is not probable that the growth was favored by storage of food material or by a high water table, for, although 1925 had more than the average amount of rain, it was preceded by the exceptionally dry year 1924. The growth may be tentatively explained in the same way as the wide ring in 1918. The slight growth in 1927 was perhaps connected with the unfavorable distribution of the precipitation—the dry summer. The relatively good growth in 1931 may have been a response to the somewhat abnormal rainfall during the period April-June. However, July and August were rainless and the summer was very hot.

It is possible that the subnormal growth in other cases than those mentioned was to a greater or lesser degree caused by insects.

The smoothed precipitation graph for Sacramento, San Francisco, and Red Bluff in northern California, which has been referred to as the " Sacramento rainfall curve " (Plate I, a), fluctuates in general harmony with the graph of the Great Basin region of northeastern California except for differences in the prominence of the maxima and the minima. The unsmoothed curves present discrepancies during the years 1893, 1897, 1901, 1904, 1905, 1907, 1913, 1915, 1917-20. The Sacramento curve permits a general comparison of the tree growth at Susanville with the rainfall for the period 1850-88. A detailed comparison is evidently not permissible. During the eighteen-fifties and sixties alternating periods of wide and narrow rings at Susanville are well matched by periods of heavy and light rainfall at Sacramento. Since, moreover, high levels of Honey Lake correspond to wide tree rings, and desiccation of the lake to minima of tree growth, it seems that heavy growth at Susanville generally represents wet years, and little growth represents dry years. During the eighteen-seventies, a decade for which significant historical data on rainfall and water supply are almost entirely lacking, there is no decided agreement nor are there marked discrepancies between the smoothed graphs for rings and rainfall. The tree growth is probably an approximate record of the precipitation. During the eighteen-eighties the smoothed curves for rings and precipitation disagree in important respects. For the first half of the decade there are no data from which to judge whether or not the tree growth reflects the rainfall; but all the five years 1885-89 were dry at Susanville, suggesting that the growth was excessive in 1885-87.

CHAPTER X

OBSERVATIONS AT LAKEVIEW, OREGON

Lakeview lies near the northern end of Goose Lake valley in south-central Oregon, at an elevation of 4950 feet. Weather records have been kept at this city since 1890, except for the years 1909-11. Radial samples were cut from stumps at several places around Lakeview, but only those of yellow pines from two localities were used by Douglass, Schulman, and Hale in compiling the accompanying growth curve. One of the localities lies in the mountains 14 miles southwest of Lakeview, half a mile west of West Side Mill, and three and a half miles south of Drew Dam at an elevation of roughly 5400 feet. The trees, spaced from three to fifteen feet, grew on the crest and on the north slope of a dry rock ridge with a very thin soil cover. They were cut in the summer of 1931. From this place the record, derived from five trees ranging in age from 308 to 402 years, has been included in the accompanying graph (Plate I, e).

The other locality, 15 miles north-northeast of Lakeview and eight miles due south of Lake Abert, lies a mile and a half east of a sawmill on the highway and is on a west slope at least 600 feet above the highway, or at an altitude of about 5000 feet. The trees grew on the gentle slopes of rather dry ridges, one or two in very shallow soil. They were spaced at varying distances from other trees. Logging on the site was done in July 1930 and earlier. Our graph includes from this locality a record based on nine trees from 175 to 428 years old.

The smoothed growth curve for the 14 trees from the vicinity of Lakeview and the smoothed graph for the October-September precipitation at that city show fairly similar trends (Plate I, d, e). However, before 1920 the maxima and minima of growth succeed the maxima and minima of rainfall; and the prominence of the maxima in the two curves differs, the growth maximum of 1894-97 being small and the growth maxima culminating in 1908 and 1913 relatively large.

The unsmoothed curves present some noteworthy differences in details. The growth was excessive in relation to the annual precipitation in 1898, 1908, 1909, 1913-17, and 1928 but was relatively deficient in 1891-94, 1896, 1904, 1907, 1925, and 1927. The ring for 1891 is narrow in spite of the fact that the rainfall was relatively most abundant during the period February to July. The temperature was neutral. That the growth depended but little on the rainfall, is further shown by the fact that the precipitation had been almost surely excessive during the preceding rainfall year 1890. The small ring of 1892 was formed during a summer of increasing drought and rather high temperature following a spring of abundant rains. The equally small growth in 1893 took place during a dry summer after plenty of rain in April. It seems but natural that the ring of 1894 should be somewhat narrow in relation to the sudden large rainfall maximum of that season. The deficient growth in 1896 cannot very well have been caused by the amount or the time distribution of the precipitation, which was especially abundant in the spring. The comparatively wide ring in 1898 was formed in spite of a very hot summer and unusually light precipitation during every month except May of the period January to September. The growth may have been favored by storage of moisture in the ground and of food material in the trees during the preceding favorable years. While it is not to be expected that the growth should fully correspond with the abrupt rainfall maxima in 1904 and 1907, the comparatively small width of the ring of 1904 may be due in part to the late spring, resulting from the excessive precipitation in February, March, and April, and to the rather dry and warm summer. The heavy growth in 1908 and 1909 is not explained by the moderate precipitation of those years, especially as the summers were warmer than usual. Perhaps it was largely caused by moisture and food material accumulated during 1907. As the food supply was consumed and the water table lowered, the tree growth decreased. Since the rainfall of 1911 and 1912, although having a good distribution, did not particularly favor the tree growth of those years, it can hardly be assumed to have promoted the growth in 1913 and the subsequent years. The wide ring of 1913 was perhaps mainly a consequence of the abundant rains in June and July. The fairly large growth in 1914, 1916, and 1917 occurred during seasons of abundant runoff, suggesting relatively heavier precipitation in the mountains than at Lakeview. The relatively wide ring in 1915 was probably due to the rather rainy and cool summer. The somewhat deficient growth in 1925 may have been a consequence of subnormal summer rainfall and depletion of moisture and of food materials, and of lowering of the trees' vitality during the severe drought in 1924. The relatively small width of the ring in 1927 was probably a result of the dry and rather hot summer. The excessive growth in 1928 occurred in spite of a dry rainfall year following upon a dry summer. To be sure, the temperature during March and May was above the normal and probably favored an early start of the growth, but the heat of July may have been unfavorable, especially since this month had only a trace of rain.

The smoothed rainfall graph for Sacramento, San Francisco, and Red Bluff (Plate I, a) also presents a general conformity with the smoothed precipitation curve for Lakeview beginning 1891 (Plate I, d), most of the maxima and minima coming at the same time and being of similar prominence. The tree growth at Lakeview may therefore be compared with the Sacramento rainfall curve for the period 1850-90. From 1850 to 1871 there is a decided agreement in the rhythm of the curves, but the first two maxima come at slightly different times in the graphs, owing to the fact that heavy precipitation in one region was counterbalanced by light rainfall in another region. As the levels of the lakes also match the widths of the tree rings, tree growth may in a general way record precipitation in the Lakeview region. During the seventies the smoothed graphs show a smaller but still rather good conformity. The traditional data on rainfall during this time are difficult to evaluate, but there is no evidence against the tree growth being a general record of the precipitation. During the years 1880 to 1885 the two curves match well, but they disagree essentially during the next ten years. However, data on the local precipitation and on lake levels make it probable that the tree growth was relatively deficient in 1880 and 1882 and relatively excessive in 1888.

The remarkable growth minimum during the eighteen-forties is of interest. The unusually low level of Goose Lake about 1850 is evidence of a long and severe drought in the region; but data on an average stand of lake levels, rainy and snowy winters, and fair pasture during the forties, together with the moderate contemporary tree-growth minimum at Susanville, suggest that the Lakeview growth minimum was exaggerated by insect ravages, fire, or the like.

CHAPTER XI

TREE GROWTH AND WATER SUPPLY

The preceding analyses reveal that at Susanville the tree growth was about proportional to the October-September rainfall during the years 1889, 1891, 1892, 1894, 1896-98, 1903, 1906, 1907, 1911-14, 1916, 1917, 1920, 1921, and 1928-30—that is to say during 21 years, or 49 per cent of the 43-year period 1889-1931. It similarly shows that at Lakeview the tree growth approximately matched the precipitation in 1895, 1897, 1899-1903, 1905, 1906, 1910-12, 1918-24, 1926, and 1929-31—23 years, or 56 per cent of the 41 years, 1891-1931, for which the comparisons were made. Only in 1897, 1903, 1906, 1911, 1912, 1920, 1921, 1929, and 1930—22 per cent of the compared years—was there correspondence between tree growth and rainfall both at Susanville and Lakeview.

At Susanville the tree growth was excessive in relation to the annual precipitation during 14 years and deficient during 8 years, or 32 and 19 per cent of the time, respectively. At Lakeview the growth was relatively either too heavy or too light during nine years each, or a total of 44 per cent of the period of comparison.

The relatively excessive growths seem to have been due largely or entirely to the following causes: comparatively heavier precipitation at the growth sites in the mountains than at Susanville and Lakeview, respectively: S. (Susanville) 1915, L. (Lakeview) 1914, 1916, 1917; a rainy spring: S. 1931; a rainy summer: L. 1913; rainy and cool summers: S. 1923, L. 1915; a rainy spring and summer and a cool summer: S. 1899; a cool summer: S. 1902; aftereffects (conservation of moisture and food materials during the preceding year): S. 1908; conservation, in spite of warm summers: L. 1898, 1908, 1909; unknown causes, perhaps thinning of the forest or relatively heavier precipitation at the growth site than at Susanville or Fort Bidwell: S. 1900, 1901, 1918, 1919, 1926; unknown causes, in spite of a dry current and preceding summer: L. 1928; unknown causes, in spite of dry springs and summers: S. 1905, 1909, 1910. If secondary specifications and factors are omitted, excessive growths seem to have been caused by the following: relatively heavier precipitation at the growth sites: S. 1915, L. 1914, 1916, 1917; favorable distribution of the rainfall: S. 1931, L. 1913; favorable distribution of the rainfall and cool summers: S. 1899, 1923, L. 1915; a cool summer: S. 1902; aftereffects or conservation: S. 1908, L. 1898, 1908, 1909; unknown causes: S. 1900, 1901, 1905, 1909, 1910, 1918, 1919, 1926, L. 1928.

The relatively deficient growths may have been chiefly or entirely a consequence of: a dry summer: S. 1927, L. 1893; a dry spring and summer: S. 1904; dry and hot summers: S. 1893, 1895, L. 1892, 1927; a dry spring and summer and a hot summer: S. 1922; a dry and warm summer and a late spring: L. 1904; a dry summer and insect injury: S. 1924; aftereffects (depletion of moisture and food materials during the preceding dry year) and a dry summer: S. 1925, L. 1925; unknown factors other than precipitation, perhaps insects: S. 1890; unknown factors, in spite of seemingly favorable precipitation: L. 1891, 1896; slowness of response to rapidly increased precipitation: L. 1894, 1907. If secondary conditions are left out of consideration, relatively small growths seem to have been due to: unfavorable distribution of the precipitation: S. 1904, 1927, L. 1893; unfavorable distribution of the rainfall and hot summers: S. 1893, 1895, 1922, L. 1892, 1904, 1927; unfavorable distribution of the rainfall, and insects: S. 1924; aftereffects and a dry summer: S. 1925, L. 1925; unknown causes, but not precipitation: S. 1890, L. 1891, 1896; slowness of response to rapidly increased rainfall: L. 1894, 1907.

The discrepancies between precipitation and tree growth (i. e. both excessive and deficient growth together), of which there are 40 cases, thus seem to have been caused by: relatively heavier precipitation at the growth sites than at the meteorological stations: 4 cases out of 40; the distribution of the rainfall: 5; the distribution of the precipitation and the summer temperature: 9; the distribution of the rains and insect injuries: 1; a cool summer: 1; aftereffects: 4; aftereffects and dry summers: 2; unknown causes, mostly not precipitation: 12; slow reaction: 2.

After this analysis of the relationship between the tree growth and the rainfall year by year, that between the prominent maxima and minima of the growth and of the precipitation should be considered. The principal maxima and minima in the Susanville curves occurred as follows:

Maxima of rainfall		1890	1895		1901		1907		1921	
Maxima of growth		....	1896		1900		1908		1921	
Minima of rainfall	1889			1898		1903		1918		1924
Minima of growth	1889			1898		1903		1916		1924

With one exception, viz. the absence of a growth maximum in 1890, the maxima and minima of rainfall and of growth matched well, though it is noteworthy that they differed in prominence and that for unknown reasons the extremes of growth preceded the extremes of precipitation in 1900 and 1916. The extremes of growth were more prominent (i. e. they were usually greater and lasted longer) than the corresponding rainfall extremes in 1889, 1900, 1908, 1921 and 1924, whereas the conditions were reversed in 1890, 1895, and 1898.

The chief maxima and minima in the Lakeview rainfall and ring curves are:

Maxima of rainfall	1894		1907		....		1921		1927
Maxima of growth	1894		1908		1913		1921		1928
Minima of rainfall		1898		....		1918		1924	
Minima of growth		1899		1912		1920		1924	

The growth maximum in 1913-16 appears to have been chiefly a consequence of rainy summers and greater precipitation in the mountains; and the preceding minimum, a curve form due to the maximum, actually represents average growth. The other seven maxima and minima of rainfall and of growth match fairly well, except that the growth lagged somewhat during most of the compared time and that the rainfall maximum in 1894 was more pronounced than the corresponding growth maximum.

At Susanville there was found to be a direct relationship between the tree growth and the annual, October-September, rainfall during 21 out of 43 years, as summarized at the beginning of this chapter. In 1904, 1927, and 1931, and probably in 1908, 1915, and 1925, the tree growth matched the moisture that was available during the growing season, though not the annual amount, while during the years 1893, 1895, 1899, 1922-24 the growth to a greater or lesser degree corresponded to the usable water supply. Thus, the tree growth matched the available amount of water notably better than it did the October-September precipitation. If the six years of the first-mentioned group and the years 1893, 1899, and 1922 of the latter group be added to the 21 years, the tree growth corresponded to the usable water supply at Susanville during 30 out of 43 years, or 70 per cent of the time. The years of discrepancy between growth and moisture were, then, 1890, 1895, 1900-02, 1905, 1909, 1910, 1918, 1919, 1923, 1924, and 1926. They are rather unevenly distributed, more than one-third falling in the decade of 1900-09. Of the enumerated 13 years with discrepancies three, or 1890, 1895, and 1924, represent years of deficient growth; the other ten, years of excessive growth. None of the discrepancies occurred in a year characterized by a discrepancy at Lakeview.

At Lakeview the tree growth was proportional to the October-September precipitation during 23 out of 41 years. In 1893, 1898, 1908, 1909, 1913, and 1925 the growth corresponded, not to the annual rainfall at Lakeview, but to the moisture available during the growing season; and it did so essentially in 1892, 1914-17, and 1927. These 12 years, added to the 23, make 35 years, or 85 per cent of the time, during which there was a relationship between the growth and the usable water supply. The six years during which the ring width did not match the moisture were thus 1891, 1894, 1896, 1904, 1907, and 1928. Of these years with discrepancies, 1928 represented excessive growth, the other five, deficient growth.

The moisture available for trees may normally be about equal to that available for pastures, although trees are tided over the dry years in part by food reserves. The water available for trees differs somewhat from that available for planted crops, for the latter includes precipitation stored in reservoirs (as, for example, autumn rains), which is largely lost for trees and pastures. Therefore, neither the moisture recorded by the tree growth nor the annual rainfall is a correct measure of the water supply usable by man.

The foregoing analysis shows that on the dry limit of the forest at Susanville and Lakeview the tree growth corresponds to the water supply available for the trees during the growing season in about 75 per cent of the years; and groups of especially wide or narrow rings correspond in a general way to pronounced and extended maxima and minima of the annual rainfall in about nine cases out of ten. The individual tree rings, however, match the October-September precipitation during only about 50 per cent of the years, or in a haphazard manner. To be sure the correspondence of maxima and minima of growth and of annual rainfall does not necessarily include prominence, duration, or full coincidence. The narrowest ring (that of 1924) seems to be a result of deficient winter precipitation, a very dry and rather warm summer, and perhaps ravages of insects. The tree growth is affected by local circumstances, the Susanville and the Lakeview ring graphs showing notable differences. The failure of the trees to register the sudden rainfall maximum in 1890 shows that serious mistakes may be made when rainfall cycles are solely postulated on the analysis of tree ring records. While tree-ring curves, like those here presented, when taken alone, permit only general and somewhat conditional conclusions concerning past rainfall fluctuations, they acquire greater significance when supported by other types of evidence.

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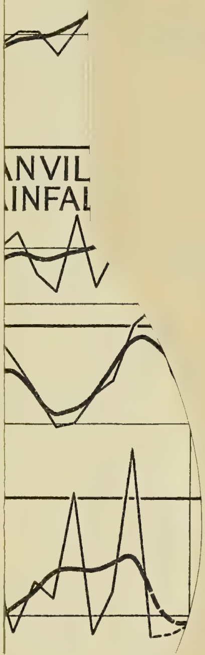

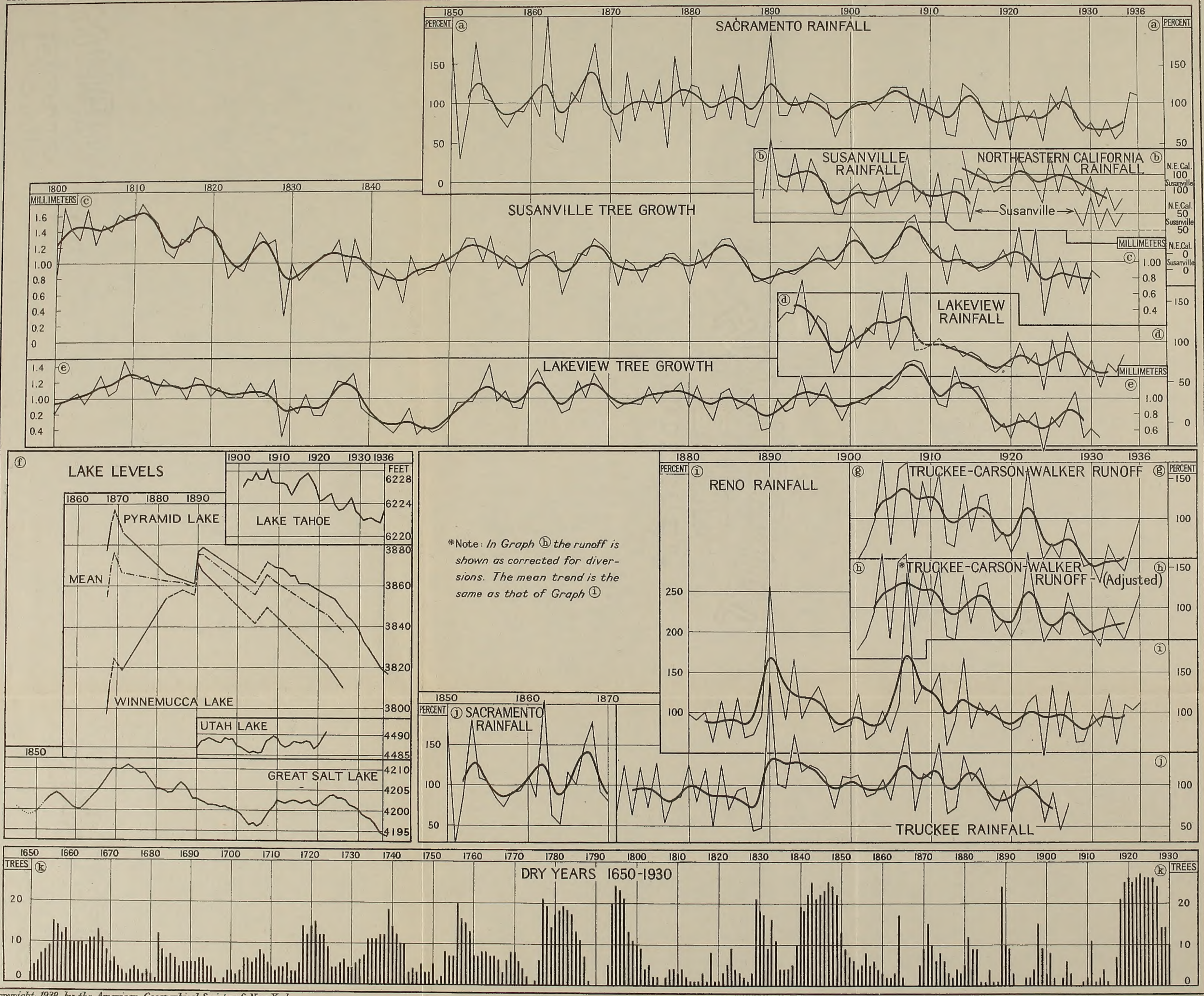

*Note: *In Graph* ⓗ *the runoff is shown as corrected for diversions. The mean trend is the same as that of Graph* ⓘ

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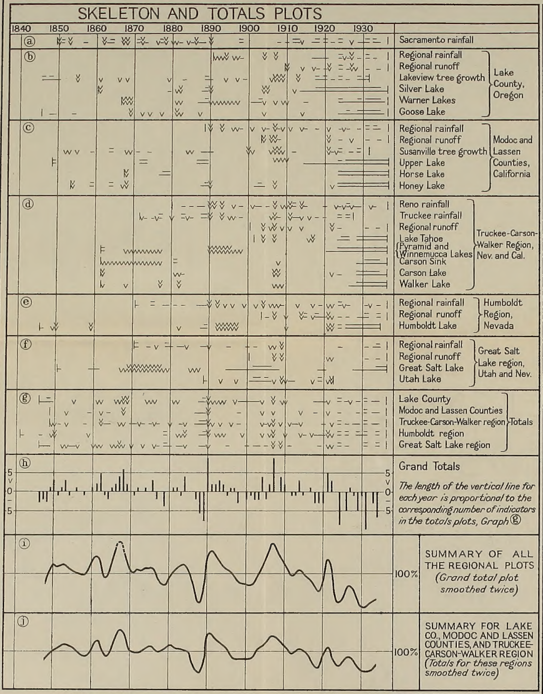
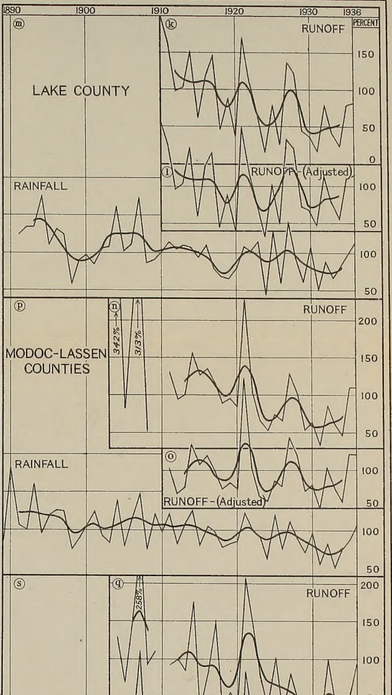
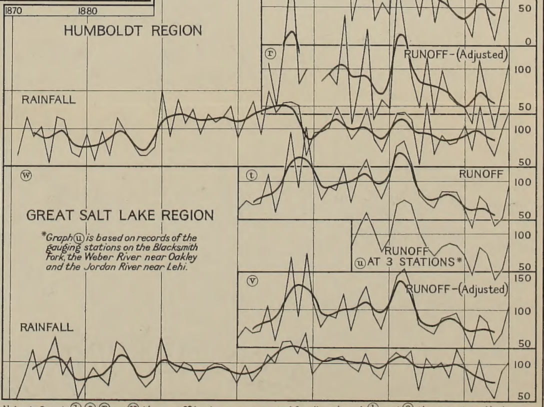


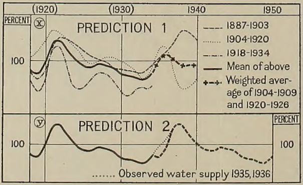




Note: *In Graphs* ⓛ, ⓞ, ⓡ *and* ⓥ *the runoff is shown as corrected for diversions. In* ⓛ *and* ⓞ *the mean trend is the same as that of the rainfall graphs for the two regions respectively; in* ⓡ *and* ⓥ *the mean trend is intermediate between that of the rainfall and that of the uncorrected runoff graphs. See text.*

EXPLANATION OF SYMBOLS IN GRAPHS ⓐ TO ⓖ

	Indicators not based on graphs	Indicators based on graphs. Percent of annual average.	
		Rainfall and tree growth	Runoff
V	Very wet year	More than 140	More than 160
v	Wet year	121-140	141-160
-	Dry year	60-79	40-59
=	Very dry year	Less than 60	Less than 40
Vertical lines indicate beginning or end of record.			



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